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## **Aspects of Understanding Electricity\***

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UNDERSTANDING AND TEACHING ELECTRICITY - A GUIDE TO THE  
WORKSHOP'S PAPERS

Reinders Duit, Walter Jung, Christoph von Rhöneck

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## 1. INTENTIONS OF THE WORKSHOP

Electricity is undoubtedly one of the basic areas of physics which receive considerable attention at all levels of physics teaching. At the primary level young children already gain some experience with simple electric circuits. At the succeeding levels, i.e. from secondary level up to university physics teaching, electricity is of pivotal importance. The "curriculum movement" of the sixties and seventies produced many new ideas on teaching electricity. Usually these ideas were not simply developed by pondering about problems of teaching electricity. Instead, try-outs in school practice were carried out with great care and expense. It appears that these efforts were not very successful. Empirical investigations carried out within the "alternative framework movement" have revealed severe learning difficulties in the domain of elementary electricity. Even in introductory physics courses at universities many "misconceptions" of students have been revealed. Quite often these students appear to have inappropriate representations of the structure of simple and branched circuits, as well as false ideas of the current's flow. Furthermore, adequate conceptions of current, voltage and resistance are very often lacking.

Two aspects moved us to plan and organize a workshop on electricity.

On the one hand we wanted to make a little contribution to the world-wide efforts to promote learning and understanding of electricity. On the other hand we intended to contribute to research within the "alternative framework movement" in general.

There are several researchers in different parts of the world who have wide experience in the area of electricity, i.e. who have carried out empirical research and who have developed ideas of teaching electricity based on the empirical results. We thought it very promising to bring members of the main

groups together. We hoped that personal contacts would promote the understanding of the different points of view and initiate international cooperation.

We therefore intended to invite at least one member of each of the main research groups working in the mentioned area. We hope that we succeeded in doing so. Of course, only groups could be considered who were known to us through their publications or personal contacts. Nevertheless, we think that the main "ideas" in the area of understanding and teaching electricity were presented in the workshop. We therefore believe that the proceedings mirror the state of the art in this area.

As far as the second of the above-mentioned intentions is concerned, we were of the opinion that research in the area of understanding electricity is very well suited to discussing general problems of research into students' alternative frameworks. Our view was influenced by the fact that much research has been done in the area of electricity and much concurrence has been demonstrated in results of different studies.

In order to meet the above-mentioned intentions closest attention was given to the following aspects:

- "stock-taking" of students "alternative-frameworks" in the area of elementary electricity, especially on basic representations and models of current flow in simple and branched circuits, as well as on conceptions of the physical concepts of current, voltage and resistance.
- "stock-taking" of research on problem solving processes in the area of elementary electricity
- discussion on methods of investigations of students' alternative frameworks and problem solving processes
- general discussion on the impact of research results on instruction
- overview of proposals for teaching electricity which take research on alternative frameworks and on problem solving

processes into consideration.

The papers presented at the workshop usually made contributions to more than one of the above-listed "major aspects of attention". Furthermore, one certain point of view (e.g. concerning electricity or on the use of a research method) or a certain conception (e.g. so-called "sequential reasoning") is discussed in several papers.

This richness of aspects discussed in the single papers did not cause severe problems during the workshop. On the contrary, it provided the participants with very different views of one single aspect.

But when preparing the proceedings we had some problems in presenting the papers in a succession which made sense for a reader not present at the workshop. Therefore, the succession of the papers as presented in the proceedings is different from the succession in which they were given during the workshop. We re-ordered the papers according to four groups. In the first one papers are to be found which focus on investigations into students' conceptions and problem solving processes. The second one contains papers which deal mainly with methods of investigations. The papers of the third group are focused on proposals for teaching electricity. A further group contains two papers which deal with some aspects of the physics of the electric circuit. Of course, there is some arbitrariness involved in attaching a paper to one of these groups. Most papers of the first group, for instance, do not only present findings of empirical research but also make some remarks on the research methods employed and on consequences for teaching. We therefore decided to make some comments on the main aspects discussed in each article. These comments are given in the following section of this introductory paper.

In a further section we will try to outline some proposals for further research in the area of teaching and learning electricity as well as in the "alternative-framework" and "problem solving" movement in general.

## 2. THE PAPERS PRESENTED IN THE WORKSHOP - AN OVERVIEW

As mentioned already we tried to cover the field of research in elementary electricity. However, this proved disadvantageous when we tried to categorize the contributions. There are many possible categories and most papers cover more than one aspect. Thus we decided to collect the contributions under quite a few broad headings. In order to help readers to see the rich interrelations between the papers the main aspects of each contribution are described. Thus we hope to mitigate the one-sidedness of the categorisation.

### 2.1. Papers focussing on students' conceptions and problem solving processes

*Some remarks on the interplay of studies on alternative frameworks (conceptions, notions, ...) and on problem solving*

Papers under this heading exemplify two main areas of research, research on representation of electricity knowledge (conceptions, 'ideas', notions, mental models), and research on problem solving in this domain. At first, these aspects may look quite different, and in fact as research interests they are different. Interest in problem solving means interest in ways of thinking, especially in ways of using knowledge to answer more or less complicated questions. Interest in representations means interest in knowledge elements, in the special rendering of knowledge in students' minds.

Yet there is a substantive relation between the two interests, which warrants a grouping together of respective papers. First, recent interest in representation research has arisen from research on problem solving. But apart from this more or less accidental fact, the relation seems to be more intimate: In order to study problem solving behaviour, one has to study the influence of knowledge elements in this

process. Formerly, problem solving psychologists were exclusively interested in general thinking processes, studying puzzle-type problems. But when they began some 15 years ago to investigate problem solving in what has been called 'conceptually rich domains', like physics, it soon became clear that the special renderings of knowledge elements are important factors in the problem solving process. They influence how the 'general' thinking processes are organized.

On the other hand, there is a tradition of research on representations arising from teacher observations: students fail to learn what they have been taught. And when teachers try to find out the reasons for the failures, they inevitably have to do two things: they have to ask questions and they have to reconstruct the thinking processes behind the answers. In other words, they end up with a variety of problem solving research.

By studying the papers, readers will find out in what measure the two research interests are actually intertwined. This is obvious with most papers. But on a more subtle level it can also be seen in so different papers as von Rhöneck's (p. 95) concentrating on semantic structures, and Riley's (p. 165) focussing on problem solving processes.

*A brief overview of areas in which investigations have been carried out*

We do not try to present a complete list of research topics treated in the investigations reported here. But a rough overview may prove useful for readers of these proceedings. First, there are investigations of the 'topological structure' of electric circuits, and its influence on reasoning and problem solving.

Second, there are papers dealing with 'mental models' of current flow.

Third, we should like to mention a number of 'basic schemata' (concerning elementary electricity) operative in student minds which emerge from the investigations:

- the source-consumer-schema
- the give-take-schema
- the share-schema
- the sink-schema
- causal schemata, e.g. the instrumental causality-schema
- misconceived 'prototypes' (in-series, in-parallel)
- the whole-part-schema, as an example of higher-order schemata important in problem solving
- the energy-transfer-schema

Finally, "sequential reasoning" should be mentioned as one of the notions which quite distinctly exhibit the intimate relation between representations and problem solving processes.

*Some remarks on papers focussing on investigations*

L. McDermott's and E. van Zee's article on "Identifying and addressing student difficulties with electric circuits"

(p. 39) opens the series of papers on investigations. Learning difficulties are described which have also been detected in several other studies. But it is most remarkable that even students at the university level after having completed college-level work have problems very similar to those of younger students. In the first part of the paper the research method "individual demonstration interview" (compare 2.2.) is reported. Among the results which are presented is, for instance, the finding also reported in other papers of these proceedings that the "first" of two bulbs in series will be brighter than the succeeding ones. Also it becomes abundantly clear that students do not sufficiently discriminate between current, energy, power, potential difference and voltage. These misconceptions reported concerning voltage and potential difference are also considerable. The authors provide a valuable summary of students' difficulties in the third part and give the outline of a curriculum constructed to avoid or overcome these difficulties.

R. Gott's contributions ("The place of electricity in the assessment of performance in science" (p. 49) and "Predicting and explaining the operation of simple dc-circuits" (p. 63) are based on the great amount of data (secondary school, ages 14 to 16) gained in the empirical studies carried out within the "Assessment of Performance Unit" in the UK. Very different research methods (e.g. questionnaires as well as practical tests) have been employed (compare 2.2.).

The first paper gives the result of items concerning connecting conditions of "consumers" to "sources" in terms of conceptual interpretations and in terms of setting up circuits in practice. After noting that "of all the questions, those involving circuit diagrams show the biggest teaching effect", the author urges a reconsideration of the "primary aims of teaching electricity".

In his second paper responses to "series" items are reported. For example, a quarter of students use the idea of constant current in the case of two bulbs, but less than 10% in the (unfamiliar) case of five bulbs. One of the important findings seems to be the fact, that "many pupils can 'do' things with circuits", but "they cannot ... explain how they work using accepted scientific ideas". Again he urges a "radical rethink of the aims of teaching electricity in a science curriculum for all pupils".

A brief overview of models of current flow detected in several studies opens D. Shipstone's paper "On children's use of conceptual models in reasoning about current electricity" (p. 73). He then presents the results of his investigations concerning models used by secondary school pupils in answering circuit items. He investigates the different popularity of five models within the age range of 12 to 17. Although there is a tendency for older pupils to use the scientific model of current flow it still depends on the specific situation which model actually is used. Shipstone concludes that at "a detailed level there are probably few pupils who will

attempt to apply any one principle, valid or not, in general". Similar findings on "model stability" are reported in other papers of the proceedings (see e.g. Duit, p. 83; Johsua, Dupin, p. 129; Kärrqvist, p. 215). Of special interest in Shipstone's paper are findings concerning "sequential reasoning" (here called sequential model) which are also given attention in other papers.

R. Duit's paper focusses on "Students representations of the topological structure of the simple electric circuit before and after instruction" (p. 83). The author reports on work done some 15 years ago with 10 to 12 year old students. Because the IPN Physics Curriculum underlying the investigations stressed the topological structure and not a model of the hidden mechanism of the electric current, many results appeared which are now seen once more as interesting and important. The paper describes the methods of investigations (e.g. a questionnaire in which the students judge whether a printed circuit will function or not, and practical tests) and reports on the changes from pre- to post-testing (e.g. before instruction 21% marked that 3 circuits with only one connecting wire will not function, but after instruction 80% did so). It appears that current flow models are less important for work on problems asking for setting up circuits than is the knowledge of the topological structure. Some of the models Shipstone (p. 73) described also appeared in this study.

There is evidence in several studies that many students' views of current flow are very near to a notion the physicist would describe as energy flow.

C. von Rhöneck's and B. Völker's paper "Semantic structures describing the electric circuit before and after instruction" (p. 95) deals with this aspect in some detail.

The authors report on the results of a comparative study in a German Gymnasium and similar French groups (grade 9, roughly 15 years). The investigation focussed on the semantic structure of the fundamental concepts of current, voltage,

resistance and energy. The results are given in diagrams (concept maps) which clearly exhibit the main features of student responses. The authors describe different views of the electric circuit, termed the "V/I/R-view" and the "energy-view" respectively. They show that without special instruction these views remain muddled, whereas after special instruction given in a German technical school current is much better discriminated from energy. The authors end up by indicating a two-level view of a teaching sequence: the level of concepts and the level of structures.

In a previous study R. Cohen (in collaboration with others) has shown that students fail in working on circuit problems, because in their view current is dominant. In his paper presented in these proceedings "Causal relations in electric circuits: students' concepts" (p. 107) the author reports on the results of efforts (in two classes, grade 11 and 12), to emphasise voltage instead of current. In the first part he describes some of the former failures. Then he indicates some of the measures taken to change the "current view" to the "voltage view" (e.g., contrary to common usage, every (dynamical) meter is taught to be seen as an instrument measuring the voltage across its terminals). Another measure was the introduction of a hydrodynamical model in order to help students understand the relation between current and potential difference, conceptualized as a sort of cause of the current. Finally results of examinations are discussed, indicating some progress by getting students "voltage minded".

H. van Aalst's contribution "The differentiation between connections in series and in parallel from cognitive mapping; implications for teaching" (p. 115) is again a paper cutting across all headings of this chapter (2.1. to 2.3.). It is included here, because we feel that its most important topic concerns an analysis of learning outcomes: He questions, as did Gott, the adequacy of the "concept-application-model" of learning outcomes, upon which most investigations in the field are based. He thinks it is an expert model which does

not easily apply to most students. He thinks the reasons for learning difficulties in the domain of elementary electricity are not primarily to be found in inadequate concepts or representations, but in inadequate teaching, based upon an inadequate model of learning outcomes. Following the concept-application-model teachers are in danger of forgetting how difficult it is to handle abstract concepts. In fact, he contends, "concepts learned have a contextual component". Upon this view, he gives a valuable list of conceptual difficulties children have with combined (series-, parallel-, and mono-) circuits. He also analyzes a number of non-conceptual difficulties. One of the most interesting is "fear for qualitative reasoning (perceived lack of accuracy)". He ends up with conclusions and implications for teaching and research. One important conclusion is that there "is a negative interference between conceptual ideas learned for series-circuits and those learned for parallel-circuits". He also warns us that "many results reported about children's conceptions, may in fact be artefacts from the questions used".

S. Johsua and J.J. Dupin ("Schematic diagrams, representations and types of reasoning in basic electricity", p. 129) treat an important topic which is often neglected in investigating students' concepts and representations, namely the confusion introduced by inadequate understanding of diagrams. A diagram is not simply a "picture", it is "a conceptual intermediary". The authors report on their investigations to find out interrelations between students' models (fluid metaphor, current reasoning) and types of diagrams (first year university students). They find conclusive evidence that forms of diagrams trigger the use of certain models (of types of reasoning). Of course, it may be questioned whether the results show shortcomings of the students or shortcomings of the diagram rules leading to physically somewhat artificial situations. Besides this, the paper confirms findings of other papers concerning sequential reasoning and the dominance of the

"current view".

As indicated above the interest in representations arose from investigations of problem solving processes, the importance of the "problem representation". Similar relations are now seen to be important in understanding and learning. M. Caillot's paper "Problem representations and problem solving procedures in electricity", p. 139) addresses this aspect in the domain of electricity. The author reports on studies (university level students), which are similar to the study of Johsua and Dupin discussed above: Problems which are physically equivalent, but presented by different diagrams, exhibit quite different responses. But his point of view is somewhat different from Johsua's and Dupin's: He is interested in the problem representation generated by the various diagrams. He concludes, that "the canonical circuit drawings play the role of prototypes of 'in-series' and 'in-parallel' concepts". The similarity of a diagram with these prototypes will lead to a building-up of the problem representation, though it may prove to be quite inadequate.

B. Andersson presents results of an area of electricity which is not treated by other authors of the proceedings, namely of an electromagnet's function. The investigation reported in his paper "Pupils' reasoning with regard to an electromagnet", p. 153) started from a chance observation in class teaching: A pupil thought an electromagnet works because a current from a wire flows into a bolt. How common is this theory? To answer the question, two problems were constructed and given to samples of students aged roughly 14 to 15 years, after instruction on magnetism and electromagnetism, including the electromagnetic field. A small sample were interviewed following their written answers. The author provides a detailed list of answer categories for each problem and the respective distributions. He concludes, that "at least half of the pupils posses the idea that current enters the bolt and causes it to become magnetic".

The author offers an interpretation based on the concept of the "experiential gestalt", in this case the gestalt of "instrumental causality", which may also prove useful in interpreting responses to circuit items: The battery is seen as the agent, the wire as the instrument, the devices as the objects acted upon. The author argues, that "the teacher is in a better position if he/she is aware of the way pupils reason", namely in a more concrete way.

The investigations on understanding problems of elementary electricity carried out by M. Riley ("Structural understanding and problem solving skill", p. 165) are different from all other studies presented here, insofar as problem solving processes are computer simulated. The presentation is set within a historical context: After decades of behaviorism we are back, in a way, to the Gestalt psychologists and educational psychologists, emphasizing "the knowledge structures that produce the behavior as well as the behavior itself (Greeno, 1976)". According to the author, the insights of the Gestaltists and other psychologists concerning the importance of structural knowledge had no bearing on instruction, because they "lacked the theoretical and methodological tools for providing explicit analyses of what constitutes structural understanding in a domain". Now, with computer simulation, we are in possession of these tools: We can elaborate in great detail different types of understanding, which even allow us to predict the results of solving specific problems. The main part of the paper consists of a description of two types of understanding, one with, the other without "structural understanding". It can be seen, that structural understanding results in much higher integration of the cognitive processes, which is an important factor in fostering meta-cognitive skills.



## 2.2. Papers focussing on methods of investigations

### *Brief overview of methods employed in the studies presented in the proceedings*

Most papers of these proceedings which present results of empirical research do not discuss the methods employed in great detail. Therefore, it is not possible to analyze adequately the interplay between aims of research and methods employed, which indeed is a central problem of research in the area of students' alternative frameworks and problem solving processes. Nevertheless, an overview on methods used in the mentioned area is provided by the papers of these proceedings.

The methods presented in these proceedings may be categorized as follows:

- questionnaires (written questions, written answers)
- interviews
- classroom observations
- observation of students carrying out experiments.

Most frequently questionnaires are used. Quite often multiple choice questions play a major role (e.g. in the paper of von Rhöneck, Völker, p. 95). But usually an explanation of the students' "choice" is requested (e.g. in B. Andersson's study, p. 153). Many questions used in the questionnaires appear to follow the tradition of test items oriented at objectives. This seems to be obvious especially in the great variety of different types of questions represented in R. Gott's papers (p. 49). There is one type of question which appears to be very popular: students are presented with printed circuits and asked to decide whether the circuit functions or not (used by Anderson, p. 153; Duit, p. 83; Gott, p. 49; McDermott, van Zee, p. 39; von Rhöneck, Völker, p. 95; Shipstone, p. 73).

Whereas the studies discussed in the preceding section (2.1.) of this chapter and in the succeeding section (2.3.)

are mainly focussed on questions which are near to usual test items two papers which are discussed in the following present questionnaire techniques revealing some aspects of the associative frameworks of concepts (see Jung's and Duit's papers below).

Sometimes advantages of questionnaires and interviews are combined. A promising strategy which has already been used by several researchers is presented here by Andersson (p. 153): after a written test has been carried out some students are interviewed. They are confronted with their answers in the test and asked for further explanations. Another strategy is to use the same questions in questionnaires and in interviews as well (as done e.g. by McDermott, van Zee, p. 39).

There are very many different interview techniques in use. Some of them appear to be very near to questionnaire techniques insofar as students are mainly freed from writing down their answers. Of course, there is an advantage of such interviews compared to questionnaires because the interviewer has the chance to ask for further explanations. Other interview techniques follow the tradition of Piaget's clinical interviews. But it has to be considered that not in all such interviews which claim to be clinical students are confronted with real experiments (as is the case e.g. in von Rhöneck's study, p. 275) and have a chance of manipulating the presented apparatus. An interesting variation of interview techniques is employed in M. Caillot's study (p. 139) in which cards are used. The cards contain printed circuits and students are among other things asked to sort the cards ("circuit sorting").

A research method which is seldom used but nevertheless provides interesting insights into learning processes running in school practice is to observe instruction and to document activities in protocols. In these proceedings this technique is used by Dupin, Johsua (p. 331) as well as by Prüm (her paper is discussed below in some detail).

It is encouraging that not only students' verbal reactions (oral or written) are employed in order to investigate students' alternative frameworks and problem solving processes in the domain of electricity. There are studies in which students' handling of experiments is investigated. In the APU surveys underlying R. Gott's papers (p. 49) experimental tasks (e.g. building up circuits, measuring current and voltage) are of considerable importance. The same holds true for Duit's studies on the topological structure of the electric circuits (p. 83). There students investigate a torch lamp and build up the illumination of a doll's house. In R. Prüm's study (see below) single students are observed when building up circuits.

*Some remarks on papers in which the main focus is on methods of investigations*

The first paper which will be given attention here is N. Fredette's paper on "The clinical interview - investigating student knowledge and ideas" (p. 175). In this paper some rules for interviews in which the interviewer tries to minimize the degree of suggestion are presented. The guiding paradigm of such interviews is "liberation of students' ideas". It is the "classical" way of using interviews. We would like to remark that some researchers have proposed interview strategies in which the interview is very deliberately suggestive. In this "non-classical" point of view the main focus is not on liberation of ideas but on finding out whether the interviewee is able to follow a specific idea or way of reasoning induced by the interviewer.

A technique in which the impact of the researcher on the investigated subject is minimized is the speaking-aloud technique presented in W. Jung's paper on "An example of the speaking aloud technique in the domain of electricity" (p. 185). Not only the method itself (i.e. its advantages and limitations) is discussed. It is paradigmatically

demonstrated how a student moves, so to speak, through the pieces of knowledge (in Jung's article on induction) he gained in physics instruction. Furthermore, the paper points out some general features of problem solving processes and throws some light on learning difficulties which have been revealed in other studies (e.g. concerning "local reasoning").

The following two papers deal with the meaning of concept names like current, voltage and energy. W. Jung presents in his paper on "Category questionnaires - the technique and some results" (p. 197) a method which gives some insight in the general categorisation of a concept, i.e. in the way a student subsumes a concept under general categories. Students are asked to put the concept names into lists of words which contain processes, things (substances) and properties (the criterion for subsuming is "best fit" into a list). It is assumed that the mentioned categories reveal important aspects of students' conceptualisations. The findings concerning current are mainly in accordance with results of other studies. Current is an ambivalent term in which the predominant aspect is not the movement of charge but the idea of a substance.

Jung's Category Questionnaire is a type of association test which gives some insight into the associative meaning of a concept. In R. Duit's paper on "The meaning of current and voltage in everyday language and consequences for understanding the physical concepts of the electric circuit" (p. 205) another type of association test is employed. Here students are asked to give free associations to words (e.g. current, voltage, energy) which are presented for approximately 30 seconds on a screen. The results concerning "current and energy" are not in all aspects in accordance with the above-mentioned results of Jung's Category Questionnaire. Duit's findings point out, for instance, that there is an overlap in the meanings of current and energy insofar as among the associations to current the word energy is frequently given and among the associations of energy the

word current. Besides presenting the method of free associations to concept names and some results gained by this method the paper discusses some general features of the impact of everyday language on learning physics. It is argued, for instance, that the "sequential reasoning" which has been detected in many papers of these proceedings (compare the preceeding section 2.1. of this chapter) may have some roots in general logical structures of everyday language.

The following two papers present research methods in which learning processes of individual students are studied by analyzing their actions e.g. when building up circuits. C. Kärrqvist starts her research work presented in the paper "The development of concepts by means of dialogues centred on experiments" (p. 215) from a constructivistic learning model. Single students are going through a series of 32 (!) experiments (e.g. building up circuits, analyzing the set up of a torch lamp). It is analyzed which ones of six models of current flow are used by the students in the single experiments. This analysis is based on videotaped students' actions (e.g. handling of materials, building up circuits, oral responses, drawings etc.). Kärrqvist finds out that it depends very much on the situation given by the specific experiment which model is used. Although there is a tendency to use more advanced models (from the physical point of view) in the course of time there are remarkable recourses to more primitive models when the specific experiment "invites" use of these models. To this extent the findings confirm results presented by Duit (p. 83) and Johsua, Dupin (p. 129) that the topological structure of a situation has decisive impact on students' problem solving in electricity. The findings furthermore confirm results on students' models of current flow (e.g. summarized by Shipstone, p. 73) and also found the conception which von Rhöneck (p. 95) calls the energy view of current.

While C. Kärrqvist arranges a fixed series of experiments in order to analyze students models R. Prüm (see her paper

"How do 12-years-olds approach simple electric circuits? - A micro study on learning processes" (p. 227)) investigates students playing with circuits following mainly their own ideas. Her interest is not fixed on the subject matter but addressed to the whole classroom situation (including variables like "classroom climate" etc.). She analyzes videotapes of a group of students in normal classrooms building up circuits. She interprets the results in the framework of sociological theories (e.g. the theory of Schütz, Luckmann). Her analysis appears to be interested mainly in describing general features of learning processes.

### 2.3. Papers focussing on teaching electricity

#### *Brief overview of the papers of this section*

The majority of papers in this group may be classified according to the following subdivisions:

- modification of childrens' intuitive ideas on electric current (Cosgrove et al., p. 247; Closset, p. 267; Shipstone and Gunstone, p. 287; Härtel, p. 343)
- teaching the voltage concept (Härtel, p. 353; von Rhöneck, p. 275)
- the importance of analogous models and the use of models as a teaching aid (Kircher, p. 299; Tenney, p. 311) Schwedes, p. 319; Dupin and Johsua, p. 331)
- the use of computers (Cohen, p. 375; Härtel, p. 343; Fredette, p. 379).

Other papers (e.g. Jung, p. 235; Steinberg, p. 363) do not fit in these subdivisions.

Nearly all the papers are related to topics which are given main attention in the sections 2.1. and 2.2. Some of these relations are mentioned in the following survey.

The conclusions of the papers lead in some cases to promising guide-lines for teaching and to concrete proposals for learning materials. Other authors present somewhat vague and open suggestions how to deal with the learning difficulties. Of course, there is no total concurrence among

the different suggestions for teaching electricity. Indeed, different points of view may lead to suggestions which are even contradictory in some aspects.

Two important points of view differ in the identification of reasons for learning difficulties. Do they stem from already existing preconceptions or from misconceptions which were induced by inadequate teaching?

An important question seems to be how to teach the discrimination of current and energy. Some authors identify the intermixture of energetic and substantial aspects in the students' concepts of current as an important issue (see Shipstone and Gunstone, p. 287; von Rhöneck and Völker, p. 95; Dupin and Johsua (p. 331). Other authors do not mention this problem (e.g. Schwedes, p. 319) or want to postpone it (see Jung, p. 235).

*Some remarks on papers focussing on teaching electricity*

W. Jung's paper "Elementary electricity: an epistemological look at some empirical results" (p. 235) does not intend to provide very concrete suggestions for teaching electricity. It rather wants to provide another view, namely an epistemological one, which permits development of new approaches to teaching electricity and also to empirical studies. The author gives a new interpretation of some well-known facts. In the view of electric current which many students hold, for instance, the aspects of storability and consumability are of considerable importance. This result of many studies is no longer interpreted on the basis of schemata or integrating views. It is now seen from an epistemological point of view. W. Jung emphasizes that the entity "electric current" is not directly observable. Therefore, the students' concepts of current refer to the circuit in a vague manner as "current in the circuit". The remedy proposed by the author is to fix the reference by speaking of "current events" in different cross sections of the circuit, and to introduce a rather unspecific meaning of

"the current" in fixing only the right category. Even regarding the concepts of voltage and resistance the vagueness of references and misleading meanings are identified as important learning difficulties.

One of the most urgent challenges to researchers in the field of students' alternative frameworks and problem solving procedures is to develop teaching strategies which take research results into consideration and indeed lead to better learning.

M. Cosgrove, R. Osborne and M. Carr present such a strategy in their paper "Childrens' intuitive ideas on electric current and the modification of those ideas" (p. 247).

Ideas about the flow of the electric current are discussed in a series of lessons. The teaching sequence consisted of a familiarization phase, a challenge phase and an application phase.

The familiarization phase provides experiences with constructing and using simple electric circuits. In the challenge phase different models of the current flow are discussed. The final evaluation over two years showed by means of interviews and written surveys that 11-years-olds tended not to have absolutely stable views. These results confirm findings of other authors (see e.g. Kärrqvist, p. 215).

The second contribution of M. Cosgrove, R. Osborne and M. Carr focusses on the application phase, namely on "Using practical and technological problems to promote conceptual change" (p. 257). They argue that a valuable physics education should relate physical science to the complex technological environment. In the three-phase teaching sequence for conceptual change the application phase is primarily seen as the place of teaching the electric current in the context of qualitative technological problems. A "tunnel monitoring problem", "traffic lights", and a "visitor at the door" are good examples for technological problems which the students obviously enjoyed and which made lasting impressions. It, therefore, appears to be valuable that the strategy presented

in the mentioned papers should be extended into the instruction of more complex concepts such as the potential differences.

The use of cognitive conflict in teaching electricity is treated in the paper of J.-L. Closset "Using cognitive conflict to teach electricity" (p. 267).

At the beginning, the author describes some examples where a conflict between experiments and preconceptions may be expected. Then the author tries to relate cognitive conflict and metacognition: The student should be conscious of his/her own natural reasoning. The task of the teacher is to discuss experiments or questions which are used to introduce a more appropriate way of reasoning. In doing so, the teacher should use "models", emphasize the limitations of the models, and teach what a model is. Again cognitive conflicts may be useful when the limitations of each model are fixed.

C. von Rhöneck's paper "The introduction of voltage as an independent variable - the importance of preconceptions, cognitive conflict, and operating rules" (p. 275) is dedicated to the development of an independent voltage concept. As has been mentioned in section 2.1. already (see especially the remarks on R. Cohens paper) there is a strong dominance of the current view among students.

Furthermore current is viewed very often within a simple source - consumer model (see e.g. Shipstone and Gunstone, p. 287). This view is not compatible with the physical view of the quantity  $I$  being constant. Therefore, a cognitive conflict may be produced when children holding the simple source - consumer view are confronted with the physical view. It is interesting that - according to results of interviews - such a conflict shows that even the students' preconceptions of voltage are affected by the simple source - consumer view.

Special efforts seem necessary to change the preconceptions and to arrive at an independent voltage concept. Some re-

sults of a teaching sequence concerning these difficulties are discussed. In this teaching sequence voltage is described as charge difference (see also Härtel, p. 353).

D. Shipstone and R. Gunstone deal with "Teaching children to discriminate between current and energy" (p.287) in a secondary school course for 12 to 13-year-olds. Several tests were provided including a circuit test, a model test, and a test asking the students to explain the processes in a circuit in their own words. A post test given 3 month after the course showed encouraging results in the model test but rather disappointing results concerning the conservation of current. The students did not have a schema valid in a broad range of circumstances. But a wider experience of applying their knowledge could yield better results.

In the following five papers models used in teaching electricity in order to ease learning play an important role. E. Kircher's paper "Analogies for the electric circuit" (p.299) opens this series. At the beginning, the author discusses the importance of analogous models for teaching on the basis of philosophical reflections. An overview of concrete water models for the electric circuit informs about the technical progress in the last decades. With the help of these models relevant features of the electric circuit can be represented. Finally, some empirical studies on the use of water models are reviewed. A synopsis follows of consequences for the use of water models in teaching basic electricity.

The paper of Y. Tenney and D. Gentner "What makes water analogies accessible: experiments on the waterflow analogy of electricity" (p. 311) views the use of analogies from the perspective of problem solving processes. The study examines possible ways of fostering analogical transfer. In two experiments the authors studied the accessibility of the water analogy for electricity. The first experiment

showed that analogical transfer did not vary with the familiarity of the base domain when an analogous problem was presented in a target domain. In a second experiment the familiarity with waterflow was induced through training. The increased familiarity with the waterflow seems to be insufficient to secure the discovery of a latent useful analogy. However, an increased familiarity improves the usefulness of the analogy if detected. These results suggest that familiarity with the base domain affects the power and not the accessibility of an analogy.

H. Schwedes ("The importance of water-circuits in teaching electric circuits", p. 319) presents a water model which has been used in school and which has been the object of studies on students' conceptions concerning the water flow in such models. It turned out that many misconceptions found in the field of basic electricity also exist in the domain of water-circuits. Nevertheless it is argued that water models may be a valuable aid in learning elementary electricity. The water model designed for instruction contains flow-watchers which show the speed of the passing water. Experimental tasks, games and problems connected with various water-circuits are seen as an autotelic educational environment. The extensive handling and discussion of water-circuits leads to a better understanding on important learning difficulties such as the principle of continuity for water. Afterwards, this principle may be extended into the electrical domain.

J.J. Dupin and S. Johsua ("Teaching electricity: interactive evolution of representations, models and experiments in a class situation", p. 331) describe the introduction of different analogous models for the electric circuit in French schools. The treatment of the relations between students' preconceptions, models, discussions and experiments appears to be the most elaborated and interesting part of this paper. The authors characterize the interpretative arguments of the students related to the "moving fluid meta-

phor" when different models of the current flow in a circuit are discussed. The students quite frequently used the energetic aspect of the moving fluid (see von Rhöneck and Völker, p. 95, Shipstone and Gunstone, p. 287) to reject the correct model. But the introduction of a mechanical analogy brought along a spectacular change in the view of this model and an acceptance of the experimental facts.

H. Härtel deals with the view of "The electric circuit as a system" (p. 343). He describes the main objectives of an IPN teaching unit. The students' preconceptions are regarded as utmost important for learning and understanding basic electricity. Local and sequential thinking (see Shipstone, p. 73) are typical of these preconceptions. The system aspect of mechanical and hydromechanical systems is activated as an integrative schema for a better understanding of the electric circuit. The mechanical model of a stiff ring plays an important part as a teaching aid. The second part of this paper describes computer-simulations of the processes in simple DC circuits. For example, six resistors of equal size can be applied in combined circuits, and the velocity of "moving electrons" is shown according to Ohm's law.

In another paper H. Härtel ("The electric voltage. What do students understand? What can be done to help for a better understanding?", p. 353) presents ideas of teaching the voltage concept. Since students generally do not have the field concept (see Andersson, p. 153), special problems arise when the abstract voltage concept is to be illustrated. The author discusses two conceptualizations which stand for the abstract potential difference: The pressure differences in water circuits are demonstrated with rather flexible tubes. The surface charges are drawn on transparencies or on a computer screen. The author discusses the surface charges in some detail in the case of simple DC circuits (see also Walz, p. 403) and in the case of a changing magnetic field in a circuit (see also Jung, p. 185).

M. Steinberg's paper "Construction of causal models: experimenting with capacitor-controlled transients as a means of promoting conceptual change" (p. 363) proposes to use a new kind of capacitor as an electric source in experiments.

In battery-centered approaches batteries are the sole sources and sole agents of propulsion of a mobile substance that is responsible for circuit processes. Sequential reasoning (see p. 15) and current as a primary concept (see Cohen, p. 107) are regarded as a consequence of these battery-centered approaches. The author proposes experiments with transient phenomena as a remedy. Capacitors of high capacitance in simple circuits provide the perception and discussion of transient phenomena as well as the discussion of the causal relationships between charge, voltage and current.

The use of computers in teaching electricity is given attention in three papers. Computer simulations presented in H. Härtel's first paper (p. 343) have already been mentioned. R. Cohen ("Using computers in teaching electricity", p. 375) describes some problems in electricity which may be solved by means of a computer. Only problems that involve mathematical difficulties are presented to the students. The solution of the problems should be illustrated in graphic displays. Some of these problems are outlined in the paper.

N. Fredette ("The use of computers as a student data check", p. 379) presents two computer programs which may be easily altered with a word processor. The programs provide the students with information which may be used to place the students' own data into a broader context. In this way, students are encouraged to examine laboratory data other than the few pieces which they collect themselves. The pedagogical dimension of this approach may be described as an attempt to encourage students to be self-critical and self-directing.

## 2.4. Papers on some aspects of the physics of the electric circuit

The following two papers do not intend to provide a brief overview of the physics of the electric circuit. They rather want to highlight aspects which do not appear to be very familiar to most physics educationalists and which may provide some new ideas of teaching electricity.

P. Farwig's article on "The energy flow in the electric circuit" (p. 393) presents an unfamiliar point of view concerning the energy flow in the electric circuit. He argues that the point of view usually taken, namely that energy flows outside the wires from the source to the consumer, is not necessarily the only one which can be justified from physical theories. On the contrary he is of the opinion that there is some arbitrariness with regard to the energy flow insofar as an energy flow within the wires can be justified too. The discussion on this point is still in progress. If Farwig's point of view is indeed correct, as it appears to be, teachers have much more freedom in teaching the energy flow in electric circuits.

A. Walz's paper on "Fields that accompany currents" (p. 403) draws attention on surface charges on conductors in which current is flowing. H. Härtel (p. 353) has given some ideas of how the point of view described by Walz may be used in order to enlarge students' understanding of current flow and of the concept of voltage.

## 3. CONCLUDING REMARKS AND SOME SUGGESTIONS FOR FURTHER RESEARCH

The papers collected in these proceedings mirror in some way the "state of the art" concerning research on learning and teaching basic electricity. The contributions of the proceedings, together with previously published papers present quite a complete survey of the students' repre-

sentations, the student's concepts, and the properties of these concepts. Although the body of knowledge available in this domain may be characterized as extensive and coherent to a certain extent, many problems are still waiting for further research. We want to conclude this introductory paper by mentioning some areas in which further research appears to be promising.

A closer look at the papers reveals a great variety of terminology. Some speak of "mental models", others of "ideas", or "views", or "gestalten", or "conceptions", or "notions", even "theories". One problem in coordinating further research may be the achievement of greater conceptual clarity. E.g., in what respect does a "mental model" differ from a "representation", or a "conception", and how important are these distinctions with respect to results of investigations?

The above remarks already emphasized a far-reaching consensus concerning "models", "representations", "conceptions", especially "misconceptions" in the domain. The reasons, however, for these "misconceptions" seem to be far less clear. In particular, researchers should get a clearer understanding of (mis)conceptions before instruction, spontaneous or otherwise, conceptions persevering in spite of instruction, and conceptions arising from instruction (i.e. from the way of teaching and from teachers' (mis)conceptions). Similar distinctions are urgently needed with respect to reasoning processes.

Another topic which should receive more attention is the relation between conception and perception, usually neglected in computer simulation research. The proceedings contain important steps in this direction. Theory building does not simply mean chance constructions, or cooking "models" by inspiration. The interactions between perception and conception may well hold the key to understanding the generation of misconceptions. Without reliable knowledge of how

and why misconceptions arise, we are in a bad position when trying to prevent them, or to eliminate them, by teaching.

A great challenge to research concerns teaching methods to avoid or to overcome learning difficulties. This holds true not only for the domain of elementary electricity but seems to be valid also for other areas of physics. Such research has to be both theoretical and empirical. On the one hand, the development of teaching and learning models based on psychological and pedagogical theories is necessary, as well as a general rethinking of the aims of teaching physics. On the other hand, more empirical evidence on the use of new teaching and learning strategies is also urgently required. Perhaps teaching in small groups may be helpful, which allows the investigation of learning biographies.

It is an open question so far whether the learning difficulties in electricity may be interpreted as a multitude of isolated facts or as a set of interdependent conceptions, i.e. a framework. In the first case, instruction may lead to an endless hurdle race. In the second case, instruction may be more coherent.

The development of an independent voltage concept within the age range of middle secondary school (14 to 16 years) appears to be unsolved so far. Since the students do not dispose of a field concept, a profound understanding of the voltage concept is hardly achievable in a first period of instruction. Further research is necessary here.

Some remarks concerning methods of empirical research may now be added. Although many different methods are available, further development is necessary. Only two examples will be mentioned here.

As has been pointed out already in section 2.2., further development of a "non-classical" interview technique appears to be promising. Such interviews very deliberately influence students in order to find out whether they are willing and



able to follow considerations or notions induced by the interviewer. They may be viewed as micro learning situations.

Somewhat weak seem to be so far association tests and similar methods for getting to know the associative framework of concept names and the general categorization of concepts.

Of greater importance than the development of further methods appears to be the general problem of the validity of the methods used in studies like those presented in these proceedings. If, for instance, H. van Aalst is right in stating that "many results reported about children's conceptions may in fact be artefacts from the questions used", research in the areas of students alternative frameworks and problem solving processes would rest on a very unstable basis. On the other hand we may find consolation in the fact that school learning is an artefact anyway. Thus, all depends upon the relevance of the "artefacts from the questions used" - and we are back at the conceptions of "non-classical" instruments of investigation, which hopefully may develop from this workshop.

# IDENTIFYING AND ADDRESSING STUDENT DIFFICULTIES WITH ELECTRIC CIRCUITS

Lillian C. McDermott and Emily H. van Zee

Recent research has led to the identification of specific difficulties students encounter in the study of physics. This detailed knowledge makes possible the design of instructional materials to meet student needs. At the University of Washington, the Physics Education Group has been engaged in a coordinated program of research and curriculum development in several topics in physics. In this paper, we briefly discuss a few difficulties identified in our investigation of student understanding of electricity and illustrate how these have been addressed in instructional materials developed by our group.

## Research to Identify Conceptual Difficulties

In this work, as in our other research, our primary data source has been the individual demonstration interview, in which we ask college students to apply concepts learned in physics class to actual physical systems. During such interviews it is possible to probe the nature of specific difficulties in detail. To assess the prevalence of a particular difficulty in different student populations, written questions are included on examinations in large introductory physics courses.

An important criterion in our assessment of student understanding in electricity was the ability to apply concepts such as current, resistance, potential difference, energy, and power in analyzing simple circuits. During interviews, we presented students with various combinations of real batteries and bulbs and asked them to predict the relative brightness of the bulbs.[1] Written versions of a few of the tasks were also administered on examinations in large lecture courses.

## Individual Demonstration Interviews

We interviewed 23 students who had completed the study of electricity in the standard introductory physics courses. Most of these students had also completed the electricity portion of the accompanying laboratory course. Student responses quoted in this paper were taken from these interviews. We also interviewed 9 prospective and practicing teachers enrolled in the laboratory-centered courses taught by our group.[2] Most of the students in our courses completed the interview tasks successfully since they had already confronted and resolved many of the misconceptions that the tasks were designed to elicit.

During the interviews, the students were presented with several tasks involving actual circuits made up of batteries and bulbs. Initially we used circuits consisting of several batteries and a number of bulbs. When these tasks proved too complicated, we simplified the circuits to combinations of a single battery and a few bulbs. We were surprised to find that students who had completed college-level work in electricity found very simple circuits such as those in Figure 1 a challenge.

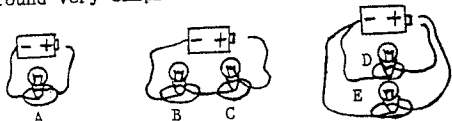


Figure 1. Interview task: predict the relative brightness of the identical bulbs in these three simple circuits.

The correct prediction, assuming ideal batteries, is that the single bulb A and the two bulbs in parallel, D and E, will be equally bright while the two bulbs in series, B and C, will be equally dim ( $A=D=E > B=C$ ).

Only one-fourth of the students who were asked to do this task responded correctly. Of those, only one gave a reasonable qualitative explanation. This student justified her prediction as follows:

S: (A, D, and E) have the same potential difference and the same resistance, so the current should be the same... (the circuit with B and C) has the same voltage and twice the resistance ...so it will cut the current in half.

About one-third of the students predicted that the "first" bulb of the series circuit would be brighter than the "second." They seemed to base this prediction on a common belief that they expressed in different ways. The following excerpts are taken from different interviews:

I: How would the bulbs within the series circuit compare?

S1: Oh, vary. The first one would be stronger...this one is in a sense getting its source first and it's taking to its maximum.

S2: You have "x" current coming through here and you think this bulb uses up some and so, there's not enough here...there's not as much current left for bulb B.

S3: B would be less bright because you always lose some energy as you go through the wires.

S4: Maybe this bulb in the first position is gobbling up the power.

Similar reasoning was applied in predicting the relative brightness of bulbs in the slightly more complicated circuit in Figure 2, in which the current splits between D and E. Since all the current flows through bulb F, it is comparatively bright. However, some students predicted:

S5: F will be dimmer than D and E...the current flowed first to D and E...they would have more difference to do what they are going to do, more push, and there would be less left for F.

S6: ...the amount of voltage drops before it gets to here (F) which is why I think that this (F) would be less.

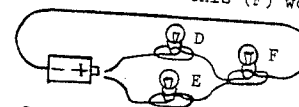


Figure 2. Circuit used in a later interview task.

The words underlined in the above statements were used by the students to refer to the "something" that they believed was being used up by the "first" bulb in the circuit - current, energy, power, potential difference or voltage. We found that many of the students used these terms interchangeably throughout the interview. Frequently, not knowing which was appropriate, the student would mention them all, in a list. Most of the students interviewed did not have a sufficiently clear understanding of these basic concepts to be able to differentiate among them in discussing real electrical circuits.

Inherent in the above responses is the belief that the sequence in which current flows through the bulbs is important. This was reflected in the emphasis the students placed on deciding the direction of current flow. Generally they used the conventional flow from the positive terminal of the battery to the negative. A common prediction was that the bulb nearest the positive terminal would be brightest and others successively dimmer. This approach is symptomatic of taking a "local" rather than a "global" point of view. In analyzing more complex circuits, students often focused on a particular bulb and its immediate neighbors rather than the circuit as a whole.

About half of the introductory physics students interviewed based one or more predictions on the belief that the battery supplies the same amount of current in all circuits. The underlined statements below are typical of the way students used this belief as a basis for their predictions on the task illustrated in Figure 1.

I: How would you compare the brightness of bulbs B and C?  
(The two bulbs in series.)

S: Well, I think C would be about as bright as A (the single bulb) but B would be less bright because you always lose some energy as you go through the wires...coming through C everything is nice and fresh...just as fresh as they left the battery...I thought that A and C would be of equal brightness because there's no reason for the current to be any less coming in here (to the "first" bulb in the series circuit, C) than it is here (to the single bulb, A) but it might be less coming out, in which case, then A and C would both be greater than B...since the current has to split in half here (at branch to the two bulbs in parallel, D and E), D and E would be less than C and A. And my prediction is that they would be less than B but I - that's the part I'm not really sure about.

This prediction ( $A=C > B > D=E$ ) was based on several related misconceptions - that the battery supplies the same current to all circuits, that current is "used up" when it flows through a bulb, and that the order of the bulb in the circuit affects brightness.

To explore further the belief that a bulb "uses up" current, we decided to ask students to predict how the reading on an ammeter would change if it were connected on either side of a bulb. We found, however, that introducing meters into the interview tasks elicited a whole new set of difficulties. Many of the students had no idea how to connect an ammeter or voltmeter or how to interpret the readings.

The view that a battery is a source of constant current continued to surface in this portion of the interview. For example, the student who drew the circuits in Figure 3 was convinced the battery supplied the same current in every circuit, even in a circuit with no bulbs.



Figure 3. Student drawing of interview task with ammeter (A)

S: ...I just don't see how I'd see that much difference whether the light bulb is there or not - isn't the current the same all the time?

I: ...what would you predict?

S: ...that the ammeter would read the same in all three circuits. Although she remembered hearing warnings about possible damage to an ammeter if there is too little resistance in a circuit, she had not understood why such warnings were necessary. This student had achieved a very high grade in her study of electricity and had completed the associated laboratory work, but she had failed to understand a basic property of circuits, that the current through a battery depends on all the components in a circuit.

#### Written Questions

To assess the prevalence of such difficulties among students enrolled in college physics courses, the interview task illustrated in Figure 1 was presented in written form on several course examinations. Although the problem appears to be so simple that instructors might be reluctant to ask it on an examination, the students in the standard introductory physics courses did very poorly. Even after having studied electricity, only about 15% of the students responded correctly. The 243 students who answered this examination question proposed thirty different orders of brightness for the bulbs.

As in the interviews, about 30% of the students predicted that one bulb in the series circuit would be brighter than the other. A typical written response was  $A > C > D = E > B$ :

S: A is brightest because it does not share any of the voltage from the power source. C is next because it is first in the series and D and E are together because they share the voltage equally while B is last for receiving the current after C has consumed much.

Although it is unnecessary for solving the problem, about 40% of the students, both in the interviews and on the written examinations, calculated equivalent resistances for the series and parallel circuits. Most of the students calculated these correctly ( $R_{\text{parallel}} = R/2$ , and  $R_{\text{series}} = 2R$ ), but did not explicitly relate these calculations to their prediction of relative bulb brightness. For those who did, the predicted order seemed to depend on whether the student used  $P = V^2/R$ ,  $I^2R$ , or  $IV$ . Most of these students used the  $P = V^2/R$  formula for power. Those who omitted the single bulb from the calculation usually predicted  $A > D = E > B = C$ . Most of the rest predicted  $D = E > A > B = C$ , that is, that the

parallel bulbs would be of equal brightness ( $P = 2V^2/R$ ) and brighter than the single bulb ( $P = V^2/R$ ) and that the series bulbs would be equally dim ( $P = V^2/2R$ ). Only a few students realized that this calculation compares total power output of the circuits and not the power output of individual bulbs. These students recognized that if the two bulbs in the parallel circuit dissipate twice the power of a single bulb alone, then the single bulb and each of the two in parallel should be equally bright ( $A=D=E > B=C$ ).

Students who used  $P = I^2R$  and equivalent resistances usually predicted  $B=C > A > D=E$ , that is that the series bulbs would be brightest ( $P = 2I^2R$ ), the single bulb medium bright ( $P = I^2R$ ) and the parallel bulbs dimmest ( $P = I^2R/2$ ). Some used proportional reasoning, such as:

S: Since  $P = I^2R$ , power is directly proportional to the resistance in the light bulb and since  $R_{\text{series}} > R_{\text{parallel}}$  the bulbs in series will be brighter than the bulbs in parallel.

As in the interviews, some of the students may have assumed that the same amount of current flowed through the battery in all three circuits. However, they may not have realized that comparing power by comparing resistances in this way is only justified if the other variable, the current, is constant.

The assumption that the current "I" was the same in the parallel and series circuits seemed to underlie the predictions by the few students who used the  $P = IV$  version of the power formula. These students predicted that the two bulbs in series and the two in parallel would all be equally bright (either  $A > B=C=D=E$  or  $B=C=D=E > A$ ).

A typical written response was:

S: A has power VI. B and C have power  $(V/2)I = VI/2$ .  
D and E have power  $V(I/2) = VI/2$ , so B,C,D, and E are the same.

Placement of bulb A, whether first or last in brightness, was usually explained in the same way - "it was the only bulb in the circuit."

#### Summary of Student Difficulties

##### 1. Lack of Adequate Model for Current Flow in Electric Circuits.

Most of the college physics students who participated in this study lacked a model that could guide them in predicting the relative brightness of bulbs in simple electric circuits. For example, in considering

the circuit in Figure 2, the students quoted earlier did not seem to envision a current that divides or recombines at branches. Many students seemed to believe that the same amount of current was supplied by a battery to all circuits and that current was "used up" as it flowed through bulbs. To these students, the direction of current flow was important as it determined the order in which current flowed through specific bulbs.

To predict relative bulb brightness correctly, it is useful to have a model of current flow in which current is not "used up" as it flows through a bulb, in which the brightness of a bulb varies with current flowing through that bulb, and in which current flowing through a battery varies with the total resistance in the circuit.

##### 2. Inability to Apply Formalism to Actual Electric Circuits

In the interviews, the students had difficulty making connections between the formalism learned in physics class and what was happening in actual circuits made up of real batteries and bulbs. Although many could remember formulas involving P, R, I, or V, they were often unable to relate the results of their calculations, or even the quantities represented by these symbols, to the actual circuits. They also had trouble translating between circuit diagrams and arrangements of wires and bulbs in actual circuits. Few knew how to connect meters to make measurements of the relevant physical quantities.

##### 3. Inability to Apply Formalism in Solving Written Circuit Problems

In predicting relative bulb brightness, many students attempted to calculate and compare the power dissipated by the bulbs. The predicted order seemed to depend on which formula for power was used and whether the student interpreted the quantities as applying to the whole circuit or individual bulbs.

##### 4. Lack of Discrimination among Related Concepts

In discussing their predictions, the students often referred to the terms current, energy, power, and potential difference or voltage. Most of the students interviewed did not seem to know which of these terms was appropriate to a given situation. Frequently they used these terms interchangeably or simply mentioned them all in a list.

##### 5. Failure to Understand the Function of Various Circuit Elements

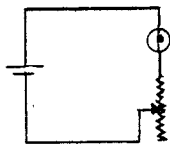
Many students failed to understand the basic functions of elements in simple circuits. For example, students generally thought of the battery as a supplier of current rather than as a constant voltage source.

### Curriculum to Address Student Difficulties

The Physics Education Group has developed instructional materials to address the issues discussed above.[2,3] Simple experiments with batteries, bulbs, and wires are used to provide the basis for the careful development of concepts such as resistance, current, potential difference, energy and power. Emphasis is placed on developing a model that enables students to predict the relative brightness of bulbs in various configurations. The examples below illustrate the nature of our approach to teaching electricity in a laboratory-centered setting.

The concept of resistance is introduced with experiments that can also be used to develop a qualitative model. The students connect a battery, a bulb, and a piece of nichrome wire in series as in Fig. 4. The length of the nichrome wire in the circuit can be varied with a sliding contact. For visual emphasis, bulb brightness rather than an ammeter is used as an indicator of current. The students can observe that the bulb dims as the length of nichrome wire in the circuit increases. This suggests

that a long nichrome wire presents a bigger "obstacle" (or resistance) to current flow than a short one. The students begin to build a qualitative model in which the current flowing through a battery is not constant but decreases as the resistance in the circuit increases.



In a later experiment, the students compare the resistance of a single nichrome wire with that of two or three wires in parallel. The brightness of a bulb in series with the wires is used as a current indicator. The students start with a single nichrome wire and then add additional wires in parallel as in Fig. 5.

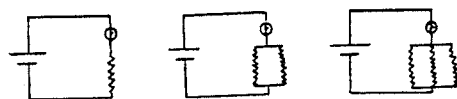


Fig. 5. Circuit to compare resistance of a single nichrome wire with nichrome wires connected in parallel

The students observe that the brightness of the bulb increases as the additional nichrome wires are added in parallel to the first wire. This suggests that nichrome wires connected in parallel present a smaller

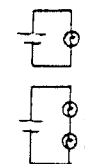
obstacle to current flow than a single wire. The students conclude that the effect of connecting nichrome wires in parallel is to reduce the resistance of the combination. Thus the model is refined to include the idea that the current varies not only with the components in the circuit but also with their configuration.

Statements typically expressed by students must be explicitly examined in some of the exercises embedded in the text. For example, the students are asked to analyze each of the following statements about the relative brightness of the identical bulbs in Fig. 6.

**Student #1:** B and C are equally bright but dimmer than A. B and C have to share the current whereas A gets all of it.

**Student #2:** B and C are equally bright but dimmer than A. B and C have to share the voltage whereas A gets all of it.

**Student #3:** A is brighter than B and B is brighter than C. B used up some of the current so less gets through to C.



A gets all the current so it is the brightest.

Fig. 6.

The correct prediction by Student #1 is accompanied by an incorrect explanation. The explanation offered for this same prediction by Student #2 differs only in use of the word "voltage" instead of "current." The incorrect prediction in the third statement reflects the belief that current is "used up" in passing through a bulb. In supporting the response of Student #2, the student must carefully distinguish between current and voltage and discuss in what sense either quantity can be considered to be "used up" or "shared" in a circuit.

Experiments and exercises of this type help students construct a qualitative model they can use in analyzing various circuits. For example, the relative brightness of bulbs in Fig. 7 can be predicted in the following way: A and B must be of equal brightness because the current splits equally between the equal resistances, A and B. Since a single bulb has a smaller resistance than two bulbs in series, more than half the current flows through C and less than half through D and E. Thus C must be brighter than A, and A must be brighter than D. Since the same current flows through D and E, they must be of equal brightness. Basing the prediction that  $C > A = B > D = E$  on calculations is much more cumbersome than using such a model.

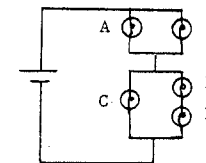


Fig. 7. Compare the brightness of bulbs.

In the process of making predictions, setting up the actual circuits, and explaining discrepancies with observations, the students can confront and resolve misconceptions such as those discussed earlier. The 9 prospective and practicing teachers who participated in the interviews discussed earlier had had this type of instruction. Thus it is not surprising that they had little trouble with the interview tasks.

It is not only in laboratory-centered courses, however, that findings from research can be used to enhance the development of conceptual clarity. Instead of using demonstrations in lecture courses merely to illustrate physical phenomena, we have designed demonstrations similar to our interview tasks to help students recognize and resolve conceptual difficulties. We regularly draw on our research experience in devising qualitative examination questions that require for solution a clear conceptual understanding. We have found that our research on student difficulties in physics has often yielded results directly applicable in both the lecture hall and instructional laboratory.

#### Acknowledgments

The authors would like to acknowledge the contributions of other members of the Physics Education Group: James Evans, Donald Greenberg, Brian Popp, and Mark Rosenquist. Curriculum produced by our group has been influenced by materials developed earlier.[4,5] The work reported in this paper was supported in part by the National Science Foundation.

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### THE PLACE OF ELECTRICITY IN THE ASSESSMENT OF PERFORMANCE IN SCIENCE

Richard Gott

#### Background to the APU surveys

The Assessment of Performance Unit was set up in the late 1970s with the brief of assessing performance in a number of key subject areas. The first full science survey took place in 1980. Since then surveys have been conducted annually; the 1984 survey will be the last before the project enters a five year research phase. The next full survey will be in 1989.

The aims of the APU at its inception included the evaluation of current instruments for assessment and the development of new ones with a view to describing performance in science and identifying areas of underachievement. The surveys utilise a national stratified sample of some one and a half to two per cent of the age cohort and encompass all children, regardless of their curriculum background.

The ages chosen for the surveys were 11, 13 and 15. Age 11 pupils are assessed immediately prior to leaving junior schools. Pupils of age 13 will have followed a more or less common curriculum in science in comprehensive and private schools, a curriculum which then diverges considerably before external examinations at 'O' and CSE level end the period of compulsory schooling at age 16.

It will be apparent then that the science to be assessed at the three ages could not be the traditional content based science taken by the more able pupils, the less able having opted for little or no science at all at age 14. The decision taken was to develop a process based framework for the assessment as outlined in Table 1.

Table 1: The categories of science performance

|                                                 |                                                                           |                           |
|-------------------------------------------------|---------------------------------------------------------------------------|---------------------------|
| 1. Use of graphical and symbolic representation | - reading information from graphs, tables and charts                      | written test              |
|                                                 | - representing information as graphs, tables and charts                   |                           |
| 2. Use of apparatus and measuring instruments   | - using measuring instruments                                             | group practical test      |
|                                                 | - estimating physical quantities                                          |                           |
|                                                 | - following instructions for practical work                               |                           |
| 3. Observation                                  | - making and interpreting observations                                    | group practical test      |
| 4. Interpretation and application               | - I interpreting presented information                                    | written test              |
|                                                 | - II applying: Biology concepts<br>Physics concepts<br>Chemistry concepts |                           |
| 5. Planning of investigations                   | - planning parts of investigations                                        | written test              |
|                                                 | - planning entire investigations                                          |                           |
| 6. Performance of investigations                | - performing entire investigations                                        | individual practical test |

A large number of questions were written and trialled before addition to a bank of items. Tests are drawn by random sampling to produce four one-hour tests in each of the categories. These tests are then distributed to subsamples of the population (light sampling) allowing the equivalent of 30 hours of testing and involving both written and practical items. One of the consequences of this is that questions in a topic area such as electricity appear only by chance. Coverage can, therefore, be incomplete.

This situation allows the test items to be cast widely enough for a broad view of science to be adopted rather than one restricted to the traditional contents of Physics, Chemistry and Biology. The papers presented here report on a small number (about 30 in all) of questions on electricity drawn from several of the categories. They are not confined, therefore, to examining pupils' understanding of concepts of current, charge, and so on, but look also at their ability to solve both paper and pencil and practical problems.

The nature of the APU testing programme produces results which are different from, but complementary to, results obtained from smaller samples. The size of the pupil sample available - typically between 200 and 900 - gives a good estimate of the performance of the population as a whole. However, it precludes the use of interviews to probe pupil understanding. Comparisons between data from APU questions and those obtained by other workers allows for a judgement to be made as to the prevalence across the whole population, and at different ages, of ideas and misconceptions unearthed during interview or action research studies.

## BASIC SKILLS

## Introduction

It may be appropriate to set the scene by describing briefly 16 questions which typify the items available for analysis - Table 2. For each question the facility for the whole sample is given, together with the data for four subgroups - those studying Physics in years 4 and 5 of secondary school (ages 14 - 16) and those not doing so, and for boys and girls. The final two columns give the non-response rates for boys and girls. It is important to bear in mind that those studying Physics are, on average, of a higher overall ability. A full discussion of all of these questions can be found in Electricity at Age 15 (DES in press).

The aim of this paper is to look in detail at a selection of the questions which address the issue of pupils' ability to set up simple circuits in both paper and pencil and practical situations - Examples 1 to 6 of Table 2.

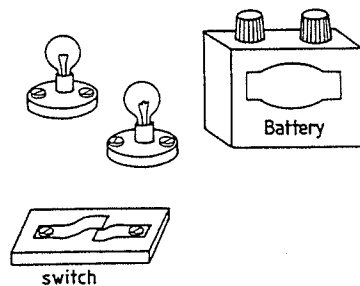
## Simple circuits

The first three questions of Table 2 are paper and pencil items which ask pupils to indicate how to connect a simple circuit. Example 1, "Connecting I", is shown below to illustrate the nature of the questions and the data available.

Figure 1: "Connecting I" (Example 1)

written

Joanne has a battery, switch and two bulbs. She wants to join them up so that when the switch is pressed BOTH bulbs light up.



Use a pencil or pen to join them up to show how Joanne should do it.

Table 2: Summary of results

| Question name             | Question content                                                                                   | Question demand                                                                          | Facility | No |    | Non response |           |
|---------------------------|----------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|----------|----|----|--------------|-----------|
|                           |                                                                                                    |                                                                                          |          | P  | B  | G            | B G       |
| 1 Connecting I            | sketches of 2 bulbs, a battery and a switch                                                        | add wires to make both bulbs light                                                       | 40       | 60 | 25 | 54           | 25 2 10   |
| 2 Connecting II           | list of apparatus, batteries bulbs and wires                                                       | indicate how to make bulb light                                                          | 62       | 79 | 50 | 69           | 56 6 11   |
| 3 Circuit error           | 5 sketches of circuits - 2 correctly wired, 3 with errors                                          | select those which will light                                                            | 64       | 75 | 53 | 73           | 55 1 0    |
| 4 Circuit labelling       | diagram of series circuit with cells, ammeter, switch & bulb                                       | identify and label components                                                            | 28       | 49 | 13 | 40           | 16 15 30  |
| 5 Circuit drawing         | sketch of circuit board - series circuit comprising 2 cells, switch, 2 bulbs and ammeter           | convert sketch to conventional diagram                                                   | 13       | 25 | 4  | 20           | 6 25 47   |
| 6 Setcico (practical)     | a) photograph of completed circuit<br>b) diagram of completed circuit<br>c) prose instructions     | set up circuit                                                                           | 70       | 84 | 64 | 40           | 51 0 1    |
| 7 Units                   | units for electric current                                                                         | select appropriate units                                                                 | 33       | 51 | 21 | 40           | 27 3 1    |
| 8 Instruments (practical) | a) an ammeter<br>b) a voltmeter                                                                    | read off set values                                                                      | 11       | 16 | 7  | 13           | 9 n/a n/a |
| 9 Amocirc (practical)     | circuit set up on bench                                                                            | measure current and voltage                                                              | 9        | 11 | 8  | 6            | 8 1 6     |
| 10 Caravan lights         | a) sketch and symbol for a number of components<br>b) sketch and symbol for a number of components | Indicate circuit arrangement for - series<br>Indicate circuit arrangement for - parallel | 62       | 8  | 49 | 71           | 52 10 10  |
|                           |                                                                                                    |                                                                                          | 20       | 43 | 8  | 30           | 13 5 16   |



Table 2 (continued): Summary of results

| Question name  | Question content                                                                | Question demand                                                                                    | Facility |    |    | No response |    |    |
|----------------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|----------|----|----|-------------|----|----|
|                |                                                                                 |                                                                                                    | P        | P  | P  | B           | G  | O  |
| 11 Copper wire | list of equipment                                                               | Indicate circuit arrangement to investigate effect on current of varying length of resistance wire | 49       | 60 | 43 | 46          | 53 | 30 |
| 12 Dimmer      | sketch of series circuit indicating variable length of resistance wire and bulb | predict effect of length on bulb brightness                                                        | 65       | 74 | 54 | 65          | 65 | 4  |
| 13 Brightness  | diagrams of 3 simple circuits indicating 2 or 3 bulbs                           | predict brightness of the bulb                                                                     | 9        | 14 | 6  | 12          | 7  | 3  |
| 14 Series I    | a sketch and diagram of series circuit indicating battery and 2 bulbs           | predict bulb brightness                                                                            | 62       | 63 | 61 | 62          | 62 | 8  |
| 15 Series II   | sketch of 3 batteries and 5 bulbs in series                                     | predict bulb brightness                                                                            | 27       | 34 | 21 | 30          | 24 | 11 |
| 16 Branching   | diagram of parallel circuit indicating cell, switch, ammeter and bulbs          | predict current at various points in circuit                                                       | 14       | 25 | 5  | 18          | 11 | 13 |

Facility - Percentage of all pupils succeeding on question

P - Percentage of those studying Physics as a separate subject

No P - Percentage of those not studying Physics as a separate subject

B - Percentage of Boys, regardless of curriculum

G - Percentage of Girls, regardless of curriculum

Table 3: Pupil responses to "Connecting I" (Example 1)

|                                      | all<br>(n = 444) | % pupils<br>P<br>(n = 188) | no P<br>(n = 256) |
|--------------------------------------|------------------|----------------------------|-------------------|
| complete series circuit              | 33               | 50                         | 21                |
| completed circuit, bulbs in parallel | 7                | 10                         | 4                 |
| completed circuit, using 1 bulb only | 1                | 0                          | 1                 |
| completed circuit in which:          |                  |                            |                   |
| - 1 bulb will light                  | 3                | 2                          | 3                 |
| - neither bulb will light            | 2                | 2                          | 1                 |
| - battery shorted                    | 28               | 19                         | 35                |
| incomplete circuit                   | 16               | 11                         | 20                |
| non response                         | 11               | 7                          | 14                |

The three columns show the percentages for: all pupils, those studying Physics (as a separate subject) and those not studying Physics.

Another question was in rather more open form; Example 2, "Connecting II".

Figure 2: "Connecting II" Example 2

written

John found two 1½ volt batteries, a bulb in a holder and several pieces of wire.

What should he do to make the bulb light?

Either say exactly what he should do, or use a sketch or diagram to help you explain.

Almost two-thirds of pupils described a circuit which would work (62% n = 303, P = 79%, no P = 50%), 90% of these accompanying their answer with either a sketch or diagram of their suggested arrangement. The higher success rate on this question may be due to the greater degree of precision needed in completing the sketch - a verbal description may in fact be hiding an incomplete understanding or the detail of how connections are to be made, or may reflect a lack of familiarity with the type of bulbholder.

Summarising the data from these questions (supplemented by data on other questions not included in Table 2) we find that:

- \* almost all pupils (> 90%) recognise the need for a completed circuit;
- \* about three-quarters are aware that the circuit must include the bulb. However, a small but not insignificant group of pupils are satisfied with any complete circuit, as in the case of the shorted battery;
- \* about two-thirds are able to describe how to connect a simple circuit but when asked to be more precise, only about half the pupils are able to draw in appropriate connections on a sketch of the components.

A number of other research studies report similar findings. Evans (1978) reports that about half the senior students at a high school (in the USA) did not know how to connect a battery and a bulb. Thiberghien and Delacôte (1976) report similar results in interviews with seven to 13 year olds.

Fredette and Lochhead (1980) gave a similar task to 57 students in a freshmen level engineering course and found about 30% of their sample were able to correctly identify errors in circuits not too dissimilar to those in Example 1, "Connecting I". They also report that approximately a fifth of their sample based their reasoning on the completeness of a circuit, even though the circuit did not contain the bulb and was in fact a direct short of the battery.

#### Using circuit diagrams

Turning now to the use of circuit diagrams, two examples were used, Examples 4 and 5 from Table 2. They asked pupils to label the components of a circuit and to translate a sketch of a circuit into a conventional diagram respectively.

Many pupils failed to score on these questions, only one-third or less getting either of them fully correct. In both of these examples, however, the non response rates were considerably higher than is usual in APU tests. This suggests that many pupils, particularly girls, were put off by the electrical context

of the questions and failed even to attempt them. The figures also contrast markedly with the two-thirds or more who were able to handle the first three questions in which only sketches were presented.

#### Setting up circuits in practice

It would seem from the results so far that a major area of difficulty experienced by many pupils is with the use of circuit diagrams as conveyors of precise information. It is of interest then to see how pupils fare in a practical activity which utilises circuit diagrams.

Figure 3: (Example 6a) "Setcirc", photographic version, practical

Choose what you need from the apparatus provided and set up the circuit as shown in the photograph.

Do all the bulbs light up when you press the switch? .....

Using the proper symbols, draw the circuit diagram of the circuit you have just made.

Figure 4: (Example 6b) "Setcirc", diagrammatic version, practical

Choose what you need from the apparatus provided, and set up the circuit shown in this diagram.

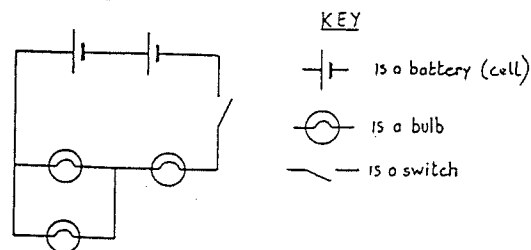


Figure 5: (Example 6c) "Setcirc", prose version practical

Choose what you need from the apparatus provided and set up the circuit following the instructions below.

1. Connect up a SERIES circuit including two batteries, a switch and two bulbs.
2. Add a third bulb in PARALLEL with one of the first two bulbs.
3. Draw the circuit diagram using the proper symbols:

The circuit shown in Figure 3 above formed the focus of three questions. The first (Example 6a) was based on a photograph of the completed circuit, the second (6b) on the circuit diagram while the third (6c) used written instructions only. Pupils were allowed six minutes to make their selection from the apparatus and connect the circuit.

Table 4: Pupil responses to "Setcirc", (Example 6a, b and c)

|                          | % all pupils            |                      |                    |
|--------------------------|-------------------------|----------------------|--------------------|
|                          | photograph<br>(n = 337) | diagram<br>(n = 732) | prose<br>(n = 344) |
| uses 2 batteries         | 96                      | 82                   | 79                 |
| 1 switch                 | 96                      | 88                   | 77                 |
| 3 bulbs                  | 90                      | 81                   | 50                 |
| correct battery polarity | 88                      | 59                   | 50                 |
| switches in series.      | 94                      | 64                   | 52                 |
| 2 bulbs in series        | 83                      | 36                   | 39                 |
| 2 bulbs in parallel      | 81                      | 22                   | 20                 |
| all correct - all        | 70                      | 14                   | 13                 |
| - P                      | 84                      | 27                   | 25                 |
| - no P                   | 64                      | 7                    | 7                  |
| non response             | 2                       | 4                    | 4                  |

**Apparatus** (for all versions of the question)

- 4 single battery holders (4 mm plug sockets)
- 4 batteries (1.5 V) in holders
- 4 bulb holders (4 mm plug sockets) with 1.25 V bulbs
- 2 switches (4 mm plug sockets)
- 10 leads (4 mm plugs) - stacking plugs (RS) all same colour

The results for the three versions of the question are shown in Table 4. The circuit components themselves are identified in the diagrammatic version of the question and were of a type familiar, at least in principle, to most pupils. Pupils were shown how to use the stacking plugs during the introduction to the practical circus. Most pupils selected the correct components to include in their circuit in all versions of the question. These figures are somewhat at odds with the figures for the labelling or drawing of similar components in Examples 4 and 5. It may be that many pupils can identify components when they can interact with the apparatus or when their chance of opting out is reduced - non response rates in the practical items are far lower.

The photographic version produced few problems for the majority of pupils, 74% setting the circuit up correctly. This exercise is, of course, only one of matching the components on the bench to those in the photograph. About 80% of pupils produced some sort of sketch or diagram but only forty per cent of them matched the photograph. Of that 40%, half were in the form of a sketch and half as a diagram - further evidence of pupils' difficulties in the translation of circuits into diagram form. As soon as either some knowledge of circuit diagrams or understanding of 'series' and 'parallel' circuits are needed this figure falls to 14% and 13% in the diagrammatic and prose versions respectively. The fact that these latter two figures are very similar further suggests that pupils understand either the meaning of both or of neither. (Eighty per cent of those who were successful in this version produced a circuit diagram with less than 20% giving a sketch.)

Of those who failed to get the circuit correct in the diagram and prose versions, about a third set up a working circuit with series components only compared to a fifth who used some parallel elements. About a third of the circuits would not work at all due to erroneous or missing connections.

### Discussion

The evidence from the first two questions ("Connecting I" and "Connecting II") together with that from the photographic version of "Setcirc" suggests that the majority of pupils - about two-thirds - are able to set up simple circuits in both paper and pencil and practical tasks. That there is a group of pupils who apparently short the battery may come as a surprise until the data from a question asking for observations to be made on a bulb are taken into account. The vast majority of pupils noted the contact in the base of the bulb; very few pointed to the dual purpose of the screw fitting acting as both retainer and conductor.

Evans recommends a very thorough familiarisation course including such apparent trivia as examining carefully the parts of a light bulb:

"Most of the students have no idea of the way the various wires inside a light bulb are connected. Lacking this understanding, how secure can they be in their understanding of 'circuit'?"

Shipstone (1984) suggests that the use of festoon bulbs may improve performance, the connections to them being far more obvious. Add to that the fact that one terminal no longer doubles up as a means of holding the bulb in place and the advantage of their use is, with hindsight, quite clear.

The adoption of such ideas can also be expected to improve performance on the use of circuit diagrams - the component symbols being more readily identified with the component itself. Nevertheless the translation of circuit diagrams is clearly an area of considerable difficulty.

A glance at the Physics and no Physics columns of Table 2, however, indicates that, of all the questions, those involving circuit diagrams show the biggest teaching effect - a case here of familiarity breeding improvement. It seems reasonable to predict that more time spent on examining circuit components and constructing circuits (although not necessarily in the artificial context of circuit boards) will improve performance. But this

surely calls into question the primary aims of teaching electricity.

The vast majority of science courses in English secondary education aim at giving pupils an understanding of circuit operation in terms, basically, of Kirchoffs' laws. Circuits to be investigated are chosen to illustrate those laws. Circuit diagrams are the shorthand for handling the ideas of current and voltage. The translation from diagram to practical circuits is only important in the context of the overall aim of acquiring understanding - translation as an end in itself is often left to vocational training.

If these aims are considered appropriate then perhaps the fact that some pupils can discuss and predict circuit operation yet be unable to set up the circuits is not too important. On the other hand, it could be argued that such abstract understanding alone is of little value in a science aimed at all pupils, the majority of whom will need above all to make circuits work rather than explain their operation.

PREDICTING AND EXPLAINING THE OPERATION OF SIMPLE DC CIRCUITS  
Richard Gott

The second of these papers concentrates on three questions which illustrate the difficulties pupils have in explaining the operation of simple circuits.

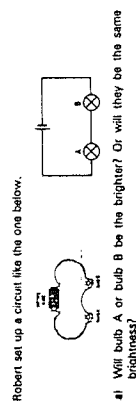
The first two questions to be described - "Series I" and "Series II" (Figures 1 and 2) - ask pupils to predict the current in a circuit and to explain their prediction. The data appear under Examples 14 and 15 in Table 2 of the previous paper.

The circuit in "Series I" is likely to be familiar to most pupils and deals with two bulbs in series. That in "Series II", on the other hand, is probably novel in that it asks for predictions about the brightness of five bulbs. The results for "Series I" are shown in Table 1.

Table 1: Pupil responses to "Series I" (Example 14)

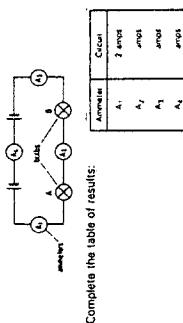
|                                   | % all pupils<br>(n = 303)  |                                 |
|-----------------------------------|----------------------------|---------------------------------|
|                                   | A and B<br>same brightness | A and B<br>different brightness |
| a) Prediction of brightness       |                            |                                 |
| Prediction only                   | 62                         | 31                              |
| Explanation:                      |                            |                                 |
| Same current                      | 24                         |                                 |
| Same power                        | 16                         |                                 |
| (Same, anything)                  | (51)                       |                                 |
| Using up current                  |                            | 6                               |
| (Using up, anything)              |                            | (12)                            |
| Nearness to battery               |                            | 10                              |
| (non response                     | 7)                         |                                 |
| b) Prediction of ammeter readings | Currents (amps)            | % all pupils                    |
| Same brightness                   | 2, 2, 2, 2                 | 28                              |
|                                   | (2, 4, 6, 8)               |                                 |
|                                   | (2, 3, 9, 6)               | 12                              |
|                                   | Other                      | 30                              |
| Different brightness              | (2, 4, 6, 8)               |                                 |
|                                   | (2, 3, 6, 9)               | 11                              |
|                                   | 2, 2, 2, 2                 | 4                               |
|                                   | Other                      | 16                              |

Figure 1: "Series I" (Example 14) written



Explain your answer.

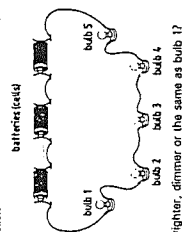
b) He then set up another circuit.



Explain your answer.

Figure 2: "Series II" (Example 15) written

Five identical bulbs are connected in a series circuit with three batteries (cells).



a) Is bulb 5 brighter, dimmer or the same as bulb 1?

Why do you say this?

b) How bright are bulbs 2, 3 and 4 compared to bulb 1?

Why do you say this?

About two-thirds of pupils (62%, P - 63%, no P - 61%) correctly predicted that the bulbs were the same brightness. The most common reasons given included the words 'the same' (51%) but only 24% said 'the same current', an equal number saying 'the same (anything)'. The 'anything' included power, energy, signal, message, force . . .

Of those who correctly predicted the brightness but attributed it to the 'same power/energy' 12% gave current predictions of 2, 4, 6, 8 amps in the circuit - presumably allowing each circuit element an equal 'share' of the current and hence an equal share of the power/energy or basing their argument on an electron flow being 'used up'.

For those predicting a difference in brightness, the most common reasons centred on either a using up of 'something' or the nearness of the bulb to the battery, again implying either a using up or 'weakening' of the 'something'.

When the number of bulbs is increased to 5, however, as in Figure 2 ("Series II"), a different picture emerges - Table 2. Only 27% now say that all the bulbs are the same brightness.

Table 2: Pupils' predictions in "Series II" (Example 15)

|                                                 | % pupils       |              |                 |
|-------------------------------------------------|----------------|--------------|-----------------|
|                                                 | all<br>(n=303) | P<br>(n=125) | no P<br>(n=178) |
| all bulbs the same brightness                   | 27             | 34           | 21              |
| bulbs 1-5 get progressively dimmer              | 26             | 21           | 30              |
| 1 and 5 same brightness, 2, 3 and 4 less bright | 13             | 7            | 17              |
| all dimmer                                      | 12             | 14           | 11              |
| other                                           | 9              | 16           | 10              |
| non response                                    | 13             | 8            | 11              |

[We have pointed to problems with the use of circuit diagrams in the first of these papers. This question, "Series II", was given in two forms - one with a sketch (as shown) and one with a circuit diagram. The results differ in detail but are broadly similar with, for instance, 31% of pupils predicting that all the bulbs would be of the same brightness in the diagram compared to 27% in the sketch versions. It would seem then that diagrammatic representation is not the overriding factor in pupil performance on written questions that its translation appears to be in practical items.]

The explanations offered can be categorised into four groups, summarised in Table 3. Figure 3 below gives a number of pupil responses to illustrate the first three of the categories of Table 3.

Table 3: Pupils' explanations in "Series II" (Example 15)

| Prediction                                                                                   | % all pupils<br>(n = 300) | Most common reasons                                                                              | % all pupils        |
|----------------------------------------------------------------------------------------------|---------------------------|--------------------------------------------------------------------------------------------------|---------------------|
| all 5 bulbs same brightness                                                                  | 27                        | same current<br>same share of power/energy<br>same voltage<br>same ('something')                 | 7<br>5<br>3<br>(19) |
| Pupil response example 1.<br>bulbs getting progressively dimmer<br>Pupil response example 2. | 26                        | mention of 'using up' or 'slowing down'                                                          | 15                  |
| bulbs 1 and 5 same<br>2, 3 and 4 dimmer<br>Pupil response example 3.                         | 13                        | a large number of answers none of them common <u>except</u> for mention of distance from battery | 9                   |
| all dimmer                                                                                   | 12                        | mention of 'using up'                                                                            | 6                   |
| other                                                                                        | 8                         |                                                                                                  |                     |
| non response                                                                                 | 14                        |                                                                                                  |                     |

Figure 3: Examples of pupil responses to "Series II", Example 15

1. *This because current in the circuit is constunly flowing and that the voltage is the same throughout the circuit.*
2. *Because the first bulb the electricity hits is 1 so the further it goes along the circuit the dimmer each bulb gets.*
3. *Because there in the same position, bulb 1-5 are taking most of the power.*

The reasons offered are similar to those for the previous example except that only seven per cent now predict that the bulbs will all be the same brightness and offer an appropriate scientific explanation.

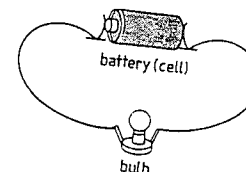
These results suggest that the majority of pupils are able to predict circuit behaviour if the circuit itself is one they have encountered before or where the options are limited. Equally, however, the majority fail when knowledge has to be applied to a new situation. Other questions, not shown for reasons of space, support this contention. Certainly, pupil success at predicting circuit behaviour is not stable across questions - the question context/content has a major effect on performance. Their explanations for the predictions are also unstable. In "Series I", 62% made the correct prediction and 24% offered an appropriate explanation. The figures for "Series II" are 27% and 7%.

The third and final question is shown below as Figure 4, "Flowcirc". In such a simple circuit it is not possible to pick out those explanations which assume that current is used up - for that we must look to the evidence of the earlier examples. Here we are primarily concerned with what pupils think is happening inside the wires and how their ideas may help us to explain their predictions. The results are summarised in Table 4. Some pupil responses which illustrate the four categories of response in Table 4 are shown in Figure 5.

Figure 4: "Flowcirc"

Paul set up the circuit shown below.

written



His friend Philip asked him to explain, as clearly and carefully as he could, what was happening in the wires to make the bulb light. What should Paul say?

Figure 5: Examples of pupil responses to "Flowcirc"

1. *He should say that a current is being passed by the battery down the wires to the bulb which causes it to light.*
2. *There are many coulombs flowing around the circuit supplying joules to the bulb. A joule is electrical energy which will light up the bulb by making the filament glow as it gets hot.*
3. *The positive charge is going through the left wire to the positive pick-up and the negative charge is going through the right wire to the negative pick-up causing the bulb to light.*
4. *The electrons in the wire are moved around the circuit by the electromotive force in the cell. In the cell they receive energy this comes from the chemical energy. When the electrons pass through the bulb they find a resistance which makes them lose their energy and it is converted into heat energy which heats up the filament to white-hot temperature (which makes it glow). The electrons return to the cell to get recharged with energy. The electrons move from the negative to the positive terminals of the cell.*

Table 4: Pupil responses to "Flowcirc"

| Pupils response example |                     |                                                                                | % all pupils (n = 303) |
|-------------------------|---------------------|--------------------------------------------------------------------------------|------------------------|
| 1                       | Single idea answers | current (lights bulb)<br>electrons (lights bulb)<br>energy/power (lights bulb) | 15<br>6<br>31          |
| 2                       | Two idea answers    | current/electrons/coulombs flow giving energy to the bulb                      | 10                     |
| 3                       | Clashing currents   | positive and negative (something) meet (lighting bulb)                         | 10                     |
| 4                       | Three idea answers  | electrons cause heat/energy due to friction/constriction                       | 4                      |
|                         | Other               |                                                                                | 16                     |
|                         | Non response        |                                                                                | 8                      |

[Performances on different groups of pupils are not available for this question which does not therefore appear in the summary table (Table 2 - previous paper).]

Half the responses to this question consisted of rather vague statements saying that 'something' (current, electrons, energy, power . . .) lights the bulbs, with no intervening arguments. One in ten pupils suggested that a current delivered energy to the bulb with only half that number attempting to say why the energy transfer occurred.

In terms of the understanding of basic ideas:

- \* a quarter of pupils use the idea of constant current in an example of two bulbs, a possibly familiar situation;
- \* less than 10% do so in the less familiar case of five bulbs in series;
- \* some 10% think that positive and negative currents flow from the ends of a battery and 'clash' in the bulb;
- \* as many as 50% give responses based on some sharing or using up of 'something' - often the 'something' is described in terms of words connected with electricity such as power, energy and electricity, but used with an imprecise or 'everyday' meaning.

Research into pupils' understanding of what is actually happening in the wires and the bulbs has thrown up a number of models. Shipstone (1984) summarises work by a number of researchers and lists four models held by pupils:

- A Current leaves the battery at both terminals.

The 'clashing currents' model [see Osborne (1981)].

- B Current flows in one direction only, becoming weaker the further it goes.

- C Current flows in one direction and is 'shared' among the circuit components.

- D The scientific view of a constant current throughout the (series) circuit.

Model A - the 'clashing currents' model - is the one most easily recognisable in pupil responses; 10% used this model explicitly in their answer. The one in 10 who predict that bulbs 1 and 5 are equally bright and 2, 3 and 4 dimmer in "Series II", may well be working on the assumption that the clashing currents also get weaker. How this view tallies with the idea that it is the 'clash' which somehow causes the brightness is not obvious. It may be that discussion of questions such as this one could be used to point to the failure of this model.

Returning to the results for "Flowcirc", it may be that the search for a stable model to describe the ideas used by the



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ON CHILDREN'S USE OF CONCEPTUAL MODELS IN REASONING  
ABOUT CURRENT ELECTRICITY

David M. Shipstone

Some models and their uses.

In recent years several studies have examined the ways in which children represent the phenomena occurring in D.C. circuits, e.g. Tiberghien and Delacôte (1976), Osborne (1981), Shipstone (1984). Five distinctly different models have been found to arise quite frequently.

a) Unipolar. There is current from one terminal of the battery only and all of this is used up. Some children think that one wire from that battery terminal to the lamp (for example) will be sufficient while others see a connection to the other terminal as necessary but passive, with no current travelling through it.

b) Clashing currents (Osborne, 1981). Current leaves the battery through both terminals and is used up.

c) Attenuation. Current travels round the circuit in one direction only, with more leaving one terminal of the battery than returns to the other. In a circuit with a series combination of identical lamps this model leads to the conclusion that those which receive the current last will get least.

d) Sharing. Similar to the attenuation model but in this case the current is regarded as being shared out equally amongst a series of identical lamps.

e) Scientific. Current travels in one direction in the circuit and is conserved.

The term 'current' has been used here for convenience. This, however, is not the term most commonly used by children at the start of their study of this subject. At that stage most refer to 'electricity' and it would be unwise to assume that this portmanteau word means 'current' to them. When children are introduced to current their views on the behaviour of 'electricity' are usually attached to this new entity, however, leading to errors in cases (a) to (d)

majority of pupils could be a vain one if in fact they have very little understanding of the underlying concept. There seems to be some evidence from the results here to suggest that there is a large population of 'floating voters' who, lacking this understanding, fall back onto the use of everyday terms. There is also the question of the stability of the model when applied to different questions - the results reported here suggest that the familiarity of the circuit may be a significant factor.

#### Discussion

Much research into pupils' understanding of science concepts is currently focussing on the 'alternative frameworks' which they bring to bear on any situation. Implicit in this is the view that pupils have more or less well entrenched ideas which they call up to mould their responses.

Examination of the scripts from APU questions in Electricity cannot deny the existence of these frameworks. However, the data suggest an alternative explanation. Many of the questions listed in Table 2 in the previous paper contain elements in common; for instance:

- \* about half the pupils put forward volts as the unit of current
- \* about half connected an ammeter to measure voltage
- \* about half of those connected the ammeter in parallel
- \* the majority of pupils use the words current, voltage, power, electricity, with little or no evidence of understanding their meaning

The common factor is one of confusion, suggesting not so much the use of incorrect ideas as the lack of any substantive and stable idea at all. Furthermore, this confusion is not restricted to pupils who are not currently studying Physics.

In "Series II", for instance, those studying Physics do perform rather better but even so only a minority refer to the current in the circuit and suggest that 'something' stays the same. An even smaller proportion (<10% of all pupils) are able to make the correct circuit predictions and offer an explanation involving current remaining the same.

What is not clear is whether it is the ideas which are confused or the vocabulary needed to make them explicit. If we examine the scripts in the light of a hypothesis that it is a confused vocabulary, and therefore place less emphasis on the terms used, many do know that something stays the same and some-

thing is 'used up' or 'shared out' - what they do not know is that these are current and energy.

If we attempt to construct models for their understanding based on our understanding of the terms involved then we may well arrive at erroneous conclusions simply because they do not know what these terms mean. Our models will then be artefacts produced by impressing our meaning for the terms on their lack of any such precision.

The picture which emerges from APU findings is one in which many pupils can 'do' things with circuits - they can connect them up, put forward solutions to problems and so on. What they cannot do is explain how they work using accepted scientific ideas, or perhaps more accurately, accepted vocabulary.

As we have already noted, the system of teaching electricity which has evolved in the science curriculum (developments) in England has one principle object in view - to present pupils with situations which will lead to their grasping the underlying concepts involved. But if they cannot understand these concepts at the deductive level - and all the evidence suggests that the majority cannot - then we have constructed an axiomatic set of rules leading nowhere.

The evidence from the scripts suggests, however, that more pupils have some intuitive understanding of how the circuits are operating. This understanding allows them to make predictions as to how a particular circuit will behave and to suggest solutions to problems. Judged against the aim of teaching deductive reasoning on the basis of accepted concepts, these intuitions are less than adequate. Judged against an aim of solving problems they may indeed be less than ideal, but if they enable the pupils to solve the problem they may well suffice.

A radical rethink of the aims of teaching electricity in a science curriculum for all pupils is needed; a rethink which looks at the most basic aims rather than one which tinkers with the means.

which are all variants of a basic source-consumer view of a circuit (e.g. Maichle, 1981).

At any one time a child, particularly a novice, might use different source-consumer models to explain what happens in different experimental arrangements. Much depends upon the assumptions the child makes about the functions of the various items which are present. One 11 year-old girl, interviewed before she started her studies of electricity, believed that the lamp in (a), Fig.1, would light while

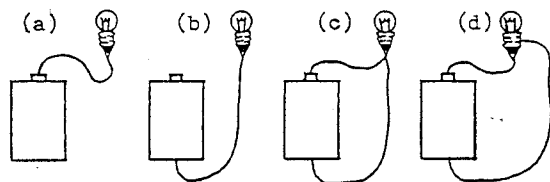


Fig.1. Some of the arrangements discussed in the interviews.

that in (b) would not: at that point in the interview she had not made up her mind about the function of the negative terminal on the battery. The lamp in (c) would light, she believed, because "the energy in the middle of the battery goes out both wires to the light bulb..... comes to the top and then lets the light go on." In (d) the bulb would light "but not as bright as the other one with both wires at the bottom (the tip of the bulb) 'cos it can't get through there (the threaded part)." In contrast to (c), in this instance "the good energy goes up here (from positive) and the one as what's been used goes back down there." So the unipolar, clashing currents and attenuation models were all applied by this one child according to the situation. This was not an isolated example and Tiberghien and Delacôte (1976) reported similar cases of 'model-switching'.

Fig.2 shows how the popularity of the various models varied with age in a British secondary school sample who answered a ten-item pencil-and-paper test in which all of the questions referred to complete circuits shown in symbolic form (Shipstone, 1984). All of these pupils had studied

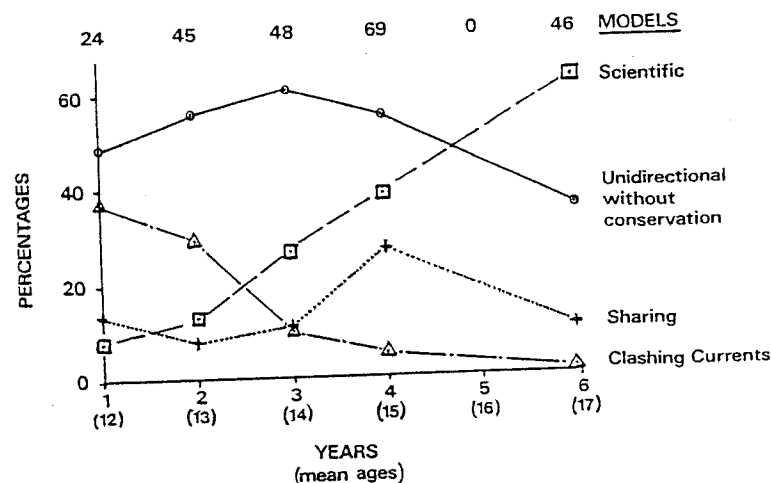


Fig.2. Variations in popularity of some models for current.

electric circuits in terms of current in the year in which they were tested. The sample sizes are given at the head of the figure.

The main problem in classifying the children's written responses was uncertainty over the meanings that they were assigning to some of the terms that they used. Another problem was that some of them appeared to use more than one model in answering the set of questions. The graphs in Fig. 2 give the best estimates for the age distributions of the models. The clashing currents model is the one usually referred to by children when they first become aware that a lamp must be connected to both terminals of a battery if it is to light and many observations can be explained in these terms. Its elimination is a consequence of instruction in the unidirectional view rather than a response by the children to experimental evidence, but it is usually replaced by one or more of the non-conservation models. The variation with age of all of these, taken together, is shown here. It was not possible in this survey to identify the unipolar model with certainty but few responses of that

type would be expected with the test items employed. Use of the sharing model, shown separately in Fig.2, enables pupils to assimilate evidence such as that identical lamps in series are equally bright without abandoning a source-consumer view but, of these three, it is the attenuation model which is the most common and most persistent. A substantial minority of pupils in year six had not abandoned this view by the end of their studies of electricity.

Presenting children with questions about complete circuits restricts the range of models they might apply. Osborne(1982) reported that only about 5% of secondary school pupils in New Zealand adopted the unipolar model when asked about a simple one battery, one lamp and two wires circuit. His evidence also revealed a decline in use of the clashing currents model very similar to that shown here. Yet behaviour suggesting use of one or other of these models, in which an MES lamp is regarded as an electrical 'sink' with one contact only, has been reported amongst high proportions of pupils near the end of compulsory education (Andersson and Karrqvist,1979) and college students in the U.S.A. (Fredette and Lochhead,1980). The construction of these lamps, which are now widely used in the teaching of electricity, presents a considerable problem, particularly since pupils see the threaded part of the lamp base as serving to hold the lamp in its socket and not as a contact. Fig.3 gives the proportions of two groups of 34 15 year-old pupils who were correct on a number of items, with MES lamps, asking 'Does the lamp light or doesn't it?' (cf. Andersson and Karrqvist,1979) and on corresponding items showing the tubular 'festoon' bulbs instead. It is important to note that none of these pupils had been taught about festoon bulbs whereas all had used the MES lamps in their experimental work. The rule that there must be two separate connections to each device if it is to play an active part in a circuit was applied very well under the favourable circumstances of (d) and (e) but the pupils were clearly misled by the appearance of the lamps in (a) to (c). Errors on these last items were not confined to

those who had elsewhere revealed their belief in a source-consumer view.

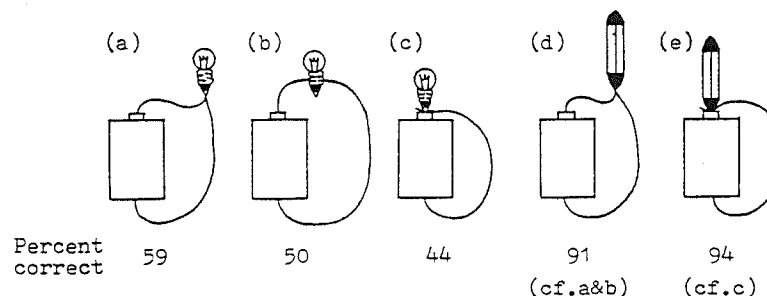
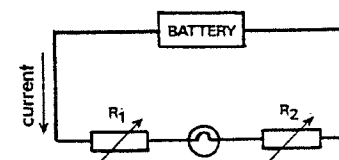


Fig.3. Responses to 'Does the lamp light or doesn't it?'

#### A model for more complex circuits.

As instruction proceeds children encounter increasingly complex circuits. Just how most of them accommodate their thinking to these new experiences is indicated by their predictions of the consequences of adjusting the variable resistors,  $R_1$  and  $R_2$ , in the circuit of Fig.4. At



**Question (in outline)**  
What will be the effect, if any, upon the brightness of the lamp, of increasing or decreasing either  $R_1$  or  $R_2$ ? Explain your reasoning.

Fig.4. Question revealing use of the sequence model.

some point in their learning almost all pupils who have a unidirectional view of current believe that it is only the variable resistor before the lamp which can affect it, e.g. 'Because  $R_2$  is only effecting the current AFTER the lamp'.

Responses of this 'before and after' nature have been referred to as indicating use of a 'time dependent model' for current (Riley et al.,1981), 'sequential reasoning' (Closset,1983) or a 'sequence model' (Shipstone,1984). The latter term will be used here, the designation as a model being well deserved. Firstly, this approach arises through

the assumption that information about any changes that take place in a circuit will only travel in the direction of the current and not against it. The imagery evoked is of a very clear, concrete nature. Secondly, it is a view which is adopted by almost all pupils at some stage and it is very persistent. Lastly, the model is applied quite widely and consistently by those who hold it.

Amongst those pupils in the cross-age study who had a unidirectional view of current the incidence of the sequence model varied as shown in Fig.5. It was also used by 7 out of a group of 18 physics and engineering graduates training to be physics teachers, emphasising its persistence.

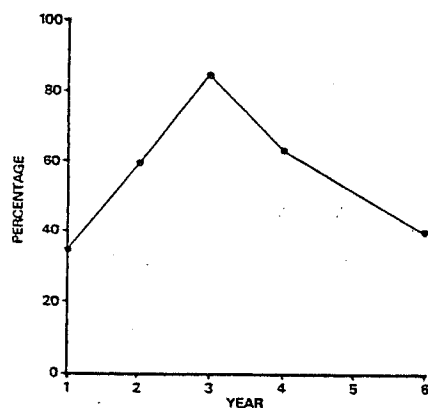


Fig.5. Variation in popularity of the sequence model.

Fig.6 sets out a range of situations in which it is very likely that the sequence model would be applied. In (a) it leads to the prediction that  $L_1$  will not alter since  $R$  comes after that lamp.  $L_2$  will not change either because the current through this lamp has already divided from that through  $R$  before the change takes place. Similar errors are found in (b) where some pupils will reason in terms of current instead of voltage and here the prediction is that neither  $V_1$  nor  $V_2$  will change. In (c) use of the sequence model leads pupils to consider only the resistors before the lamps, so here they predict that the lamps in (ii) and (iii)

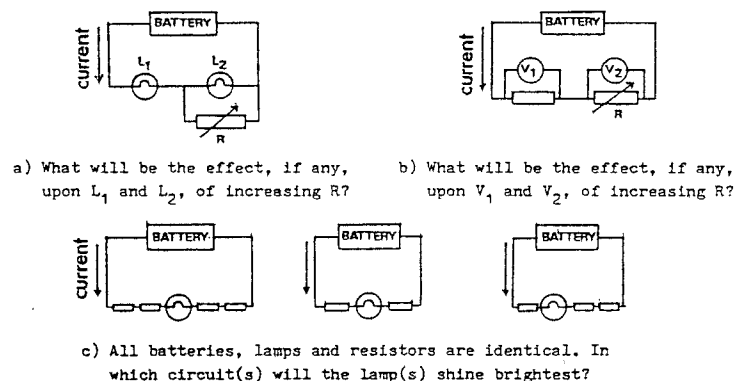
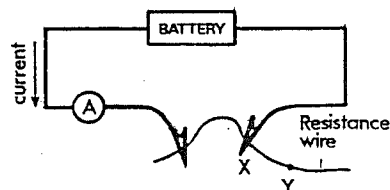


Fig.6. Questions in which the sequence model is commonly applied.

will be equally bright. In some cases pupils holding the sequence model will make unconnected errors and others will answer correctly through the use of algorithms, e.g. that 'most current takes the easier path'. Nevertheless, in the fourth year sample, 72% of the errors made by those holding the sequence model predicted that  $L_2$  in (a) would not alter and 59% of these pupils definitely applied the model in concluding that  $L_1$  would stay at the same brightness. Similar results were obtained in (b) and (c).

However, A.P.U. Report No.3 (DES, in press) draws attention to one situation, shown in Fig.7, in which use of the sequence model appears to be less common. This was therefore given to one half, randomly selected, of those pupils



Question (in outline)  
What will be the effect, if any, upon the ammeter reading, of sliding the crocodile clip at  $X$  along the wire to  $Y$ ?

Fig.7. A simple question about varying resistance.

studying physics in the fourth year of a comprehensive school, while the other half were given a question testing for conservation of current in a series circuit with two lamps. For both groups the second question, over the page, tested for use of the sequence model with the circuit of Fig.4. The frequencies entered in Table(a) show that these pupils used the sequence model significantly less often with the circuit of Fig.7 than with that of Fig.4 ( $p < 0.01$ ), while those in Table(b) show that the responses to Q.2 were not significantly influenced by the encounter with Q.1 (Fig.7).

|              | a) Response type |       |                          | b) Response to Q.2 |       |
|--------------|------------------|-------|--------------------------|--------------------|-------|
|              | Sequence         | Other |                          | Sequence           | Other |
| Q.1 as Fig.7 | 10               | 22    | Q.1 as Fig.7             | 24                 | 8     |
| Q.2 as Fig.4 | 24               | 8     | Q.1 on conserv-<br>ation | 18                 | 14    |

That pupils see these as very different questions was highlighted by the fact that not one child, after answering Q.2, turned back to alter his/her response to Q.1. The differences may be the result of the two representations used for variable resistors and the much clearer 'before and after' situation confronting the pupils in Fig.4. In Fig.7 the presence of a battery, a lamp and an increased resistance permits immediate closure without consideration of the circuit geometry. Whether or not a pupil resorts to the sequence model appears to depend upon the complexity of the circuit.

#### Association between the sequence and attenuation models.

Riley et al.(1981) pointed out that non-conservation of current is a logical consequence of what they called the 'time-dependent' model, according to which a resistor, for example, must alter the current which flows through it if it is to have any effect at all. An association between the sequence and attenuation models would therefore be expected.

The contingency tables below show how use of the sequ-

ence model was associated with use of the attenuation model for current, for (a) a group of year six pupils at the end of their study of electricity and (b) a mixed-subject group of post-graduate trainee science teachers. The association is significant in both cases ( $p < 0.01$ ). With fourth year pupils and younger no evidence of any association was found.

|                            | Sequence model |         |                            | Sequence model |         |
|----------------------------|----------------|---------|----------------------------|----------------|---------|
|                            | +              | -       |                            | +              | -       |
| Attenu-<br>uation<br>model | +              | 8    3  | Attenu-<br>uation<br>model | +              | 9    2  |
|                            | -              | 4    20 |                            | -              | 6    14 |

a) Year 6 pupils

b) Post-graduate sample

In the case of novices almost all who use a unidirectional model do not conserve current and yet relatively few show evidence of having developed a sequence model. For these, it seems, non-conservation arises through intuitive source-consumer beliefs.

Earlier it was stressed that pupils may employ different conceptual models according to the circumstances with which they are confronted. It is probable, therefore, that they develop the sequence model independently of their other beliefs when they encounter complex circuits. In these situations, though, its application leads to expectations which conflict with the principle, strongly emphasised by teachers, that current is conserved and belief in the attenuation of current would be expected to persist where the conflicts are not resolved.

#### Concluding remarks.

Models have been described which are used by school-children, and sometimes by students at more advanced levels, to predict, and in some cases to understand and explain, D.C. phenomena. Whereas it is not the case that children normally commence their studies with a firm conviction about the validity of any of the detailed models described, most do begin with a source-consumer view which they hold

very tenaciously, though its exact form may vary over time and from situation to situation. At a detailed level there are probably few pupils who will attempt to apply any one principle, valid or not, in general. Despite the evidence for model-switching the models do provide a useful guide to the main lines that pupils might follow in their reasoning.

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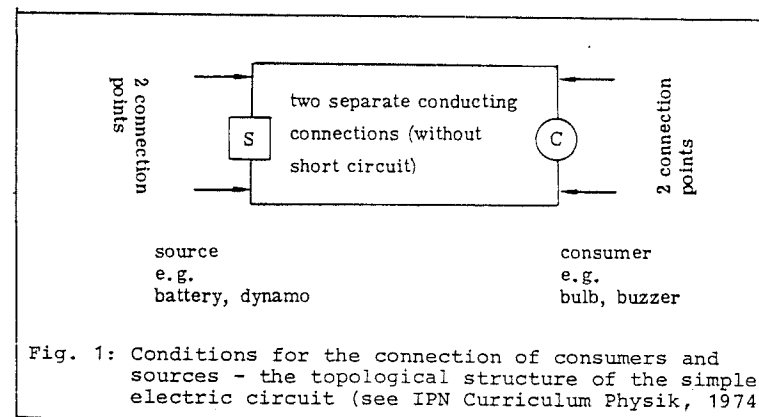
#### STUDENTS' REPRESENTATIONS OF THE TOPOLOGICAL STRUCTURE OF THE SIMPLE ELECTRIC CIRCUIT

Reinders Duit

##### 1. Introductory remarks

Some 15 years ago we developed a physics curriculum for grades 5 and 6 (i.e. for 10 to 12 year old students). Our instruction unit on the simple electric circuit within this curriculum focussed on "connecting conditions" between sources and consumers, i.e. on the topological structure of the simple electric circuit. Empirical investigations during several trial runs of the instruction unit studied students' representations of this topological structure. The results of these studies will be summarised here.

##### 2. Main ideas of our instruction unit on the simple electric circuit



In the very beginning of our instruction unit the students "play" with a battery, a bulb and some metal wires. They are asked to find out possibilities to light up the bulb. Further students' experiments with simple everyday equipment (such as different batteries, bicycle dynamo, different bulbs,

buzzer and the like) lead step by step to conditions for the connection of sources and consumers as portrayed in fig. 1. This topological structure provides operating rules which should enable students to build up circuits. A model of current flow is given only little attention at the very beginning of the instruction unit. Students at this age level (approximately 10 to 12 years old) are much more interested in simply learning the above-mentioned operating rules in order to be able to build up circuits than in explaining these rules with the aid of a flow model. Of course, such a model is also introduced during instruction but only very carefully step by step. Not only circuits as simple as portrayed in fig. 1 are contained in the instruction unit but also circuits with one or more switches as well as with one or more bulbs (both in parallel and in series).

The instruction unit on the simple electric circuit as outlined above is the basis for dealing with concepts of electricity in the subsequent years of our physics curriculum for grades 5 to 10. Härtel's papers presented at this conference deal with some major features of these subsequent units.

### 3. Overview of methods for evaluation of the unit on the simple electric circuit

The findings on students' representations of the simple electric circuit which will be presented in section 4 of this paper are based on structured classroom observations (including protocols of lessons) and on results of the following tests.

#### (a) paper and pencil test oriented to the objectives

The topological structure as portrayed in fig. 1 was tested in two ways.

Firstly, a number of circuits were printed in the test manuals (see some circuits in fig. 2). The students were asked to mark whether the circuits would function or not. The main variables included in the different circuits were the following:

- functioning circuits (see e.g. fig. 2a)
- circuits with only one connecting wire (see e.g. fig. 2d)

- circuits with two connecting wires in which only one connection point of the source or the consumer is used (see e.g. fig. 2b)
- circuits with insulators (see e.g. fig. 2c).

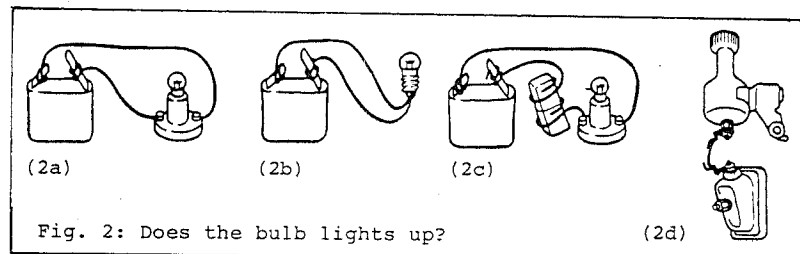


Fig. 2: Does the bulb lights up?

Secondly, the students had to draw connections between sources and consumers printed in the test manuals (see fig. 3). In order to investigate notions of current flow tasks such as the following were included: "How many wires does the cable of a standard lamp have?"

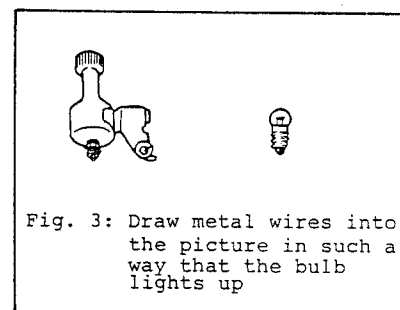


Fig. 3: Draw metal wires into the picture in such a way that the bulb lights up

Please explain why this is so!" - "Please explain why a bulb lights up when it is connected to a battery!". Further tasks in the test dealt with conductors and insulators as well as with circuit diagrams, the concept of short circuit and switches.

#### (b) electric torch test

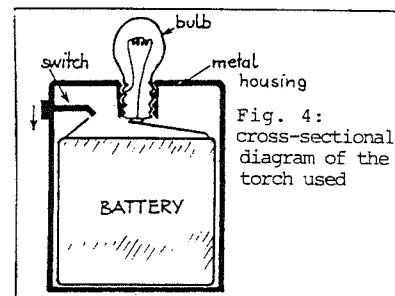


Fig. 4: cross-sectional diagram of the torch used

Students investigated the electric torch portrayed in fig. 4. They were asked to make a drawing of the torch and to mark in red the electric circuit in their drawings. The test provides information on students' ability to recognize the topological structure of the



electric circuit in a piece of everyday equipment.

#### (c) doll's house illumination test

The main objective of our unit was to enable students to build up functioning circuits. Results from paper and pencil test are not suited to evaluate this objective. We therefore included a "practical" test. The students were asked to build up circuits. As a "frame of motivation" the illumination of a doll's house was employed. The students were given a battery, a number of metal wires and one of the boards presented in fig. 5. They were asked to build up circuits so that lamp A

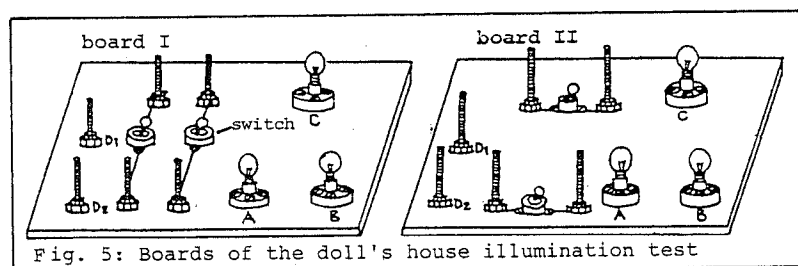


Fig. 5: Boards of the doll's house illumination test

and lamp B would light up (as bright as possible) when one of the switches was closed, and with lamp C lighting up independently when the other switch was closed. Two versions of the board were used in order to investigate effects of the topological structure of the boards on solving the tasks.

#### 4. Findings concerning students' representations of the topological structure of the electric circuit

The paper and pencil test outlined in section 3 has been used in several trial runs of the curriculum unit. Data are available from the development of the curriculum (several samples of approximately 300 to 400 students each) and from a trial run in many schools of the Federal Republic of Germany which used the published curriculum materials (approximately 5000 students).

The "torch test" and the "doll's house illumination test" have been used only in a trial run during curriculum development (approximately 300 students).

#### 4.1. Students' judgements of the function of circuits

Before physics instruction students' knowledge of the connecting conditions appears to be very limited. Although 62% of the students marked circuits with two connections as functioning and although 54% marked in another task that the cable to a standard lamp has two (or three) wires, most of the students did not appear to be convinced that two connections are really needed. The great majority of students seemed to think that one wire is sufficient in order to supply the consumer with electricity (similar findings are reported by other papers in these proceedings).

|                          |                           |                                                                                                                                                                          |
|--------------------------|---------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 62%<br>in the<br>pretest | 96%<br>in the<br>posttest | marked that 3 circuits with two connecting wires (metal wires) between source and consumer (see one of these circuits in fig. 2a) <u>will function</u>                   |
| 17%<br>in the<br>pretest | 78%<br>in the<br>posttest | marked that 3 circuits in which <u>only one connecting point of the source or the consumer is used</u> (see one of these circuits in fig. 2b) <u>will not function</u> . |
| 21%<br>in the<br>pretest | 80%<br>in the<br>posttest | marked that 3 circuits with only <u>one connecting wire</u> (see one of these circuits in fig. 2d) <u>will not function</u> .                                            |

Table 1: Results concerning students' judgements of the function of circuits  
161 classes, grades 5 and 6, approximately 5000 students.  
Instruction according to the unit outlined in section 2. For more details of instruction and the results gained see IPN Curriculum Physik (1974).

After physics instruction most students did quite well in the tasks presented in fig. 2 and in other tasks concerning the topological structure of the electric circuit (see e.g. the task in fig. 3). It therefore appears justifiable to conclude that most students gained a representation of the topological structure of electric circuits (as portrayed in fig. 1) which

enabled them to deal successfully with the tasks presented in their test manuals.

The general features of the above - outlined findings of pre-test and posttest are not only valid for the specific sample mentioned in table 1, but also for all other samples investigated in our studies.

In a doctoral thesis, Niedderer (1972) presented to students 60 tasks as portrayed in fig. 2. His findings point out that the correct judgement of functioning is not only dependent on the subject matter but is also considerably influenced by the symmetry of the circuits. There was a tendency for circuits with a high degree of symmetry to be judged as functioning more frequently than circuits with a lower degree of symmetry.

#### 4.2. Results on the limited use of a current flow model

There is evidence from results of the paper and pencil test that at the very beginning of teaching electricity, a flow model of the electric circuit does not aid students' judgments of the functioning of circuits and other applications of the topological structure of the electric circuit as portrayed in fig. 1.

In the pretest there were significant correlations between the above - mentioned tasks concerning the topological structure (see fig. 2 and fig. 3) and also significant correlations between the tasks concerning current flow. But there were no significant correlations between the two groups of tasks (for more details see Aufschnaiter et al., 1970). Results gained between the first and the second part of the instruction unit also revealed almost no connection between the two groups of tasks. Only in the post test and in a long-term retention test (approximately 6 months after the post test) did significant correlations appear, some in the post test and a considerable number in the long term retention test (see Duit, Niedderer, 1970). Considerable time therefore seems necessary to make the flow model a useful tool for students beginning to learn electricity. This not only became evident in the above-

mentioned tasks. In general, correlations between the group of tasks concerning notions of current flow on the one hand and other tasks on the other (e.g. concerning the concepts of conductor, insulator and short circuit) became slightly higher during instruction and considerably higher during the period between the post and long-term retention test.

#### 4.3. Students' models of current flow

Students' models of current flow have been investigated in several studies (see e.g. the overview given by Shipstone in these proceedings). In our research work, such models have been studied by analysing protocols of classroom discussions and students' answers in tests. Although no formal quantitative analysis has been carried out, the models revealed may be of interest. Before physics instruction most students appear to have the idea that one connection between source and consumer is sufficient (see 4.1.). Some of these students have a "pipeline model", i.e. they seem to draw an analogy to fuel flow in pipelines (or the like).

After physics instruction most students know that two connections between source and consumer are needed (see 4.1.). But only a very small minority seems to have the correct physical model. Much more frequently other models appear to be employed (see IPN Curriculum Physik, 1974). They also have been revealed in other studies:

##### o The "current is consumed" model

In this model current is flowing in a circle, i. e. from the source to the consumer, through one of the connections and back to the source through the other connection. But current is partly used up in the consumer. Therefore, only the remaining current flows back to the source.

##### o The "two kinds of current" model

In this model two kinds of current are conceptualised. In one "type" of this model, current is flowing in both connections from the source to the consumer. Some students speak of "plus current" and "minus current". In the consumer, both currents meet. There are some "amusing" notions of the currents' meeting. Some students appear to employ an analogy to a chemical reaction (the two currents come together and produce, for instance, light). Other students expressed that the currents clash together so that flashes are sparkling in the bulb.

A very different type of the "two kinds of current" model is used by some students. They employ an analogy to fuel supply of a combustion engine. They are of the opinion that a kind of fuel is flowing from the source to the consumer through one of the connections. The other connection is responsible for exhaust transfer.

#### 4.4. Some results of the "electric torch test"

In the torch test (see fig. 4) the students had to identify the parts of the electric circuit they had met in instruction, namely the battery, the bulb, the switch and the connections between battery and bulb. The results point out that the students had some difficulties with this task. Out of 300 students (grades 5 and 6) who took part in this test only 70% were able to put the battery into their drawings of the torch. The switch and the bulb were drawn by only approximately 50%. Solely 10% drew the bulb in detail (i.e. including the filament and its connections to the bulb's socket). These findings are somewhat surprising because these students did quite well in the tasks of the paper and pencil test concerning the topological structure of the electric circuit. The students had to mark in red the electric circuit in their drawings. They appear to have great difficulties in recognising the topological structure here, although most of them were able to do it in tasks of the paper and pencil test. The battery was marked by approximately 70% as part of the circuit, the switch by 40% and the bulb by 25%. Details of the current's path through the bulb (e.g. including the filament) were marked by only 5%. Furthermore only 20% marked the metal housing as part of the circuit.

#### 4.5. Some results of the "doll's house illumination test"

This test provides empirical evidence of students' ability to build up circuits. Table 2 presents the main results for the two kinds of boards used (see fig. 5).

|                  |                                   | board<br>I | board<br>II |    |
|------------------|-----------------------------------|------------|-------------|----|
| bulbs<br>A and B | correct connection to the battery | 53%        | 52%         |    |
|                  | bulbs A and B in parallel         | 28%        | 12%         | *  |
|                  | correct use of a switch           | 9%         | 40%         | ** |
| bulb C           | correct connection to the battery | 69%        | 78%         |    |
|                  | correct use of a switch           | 11%        | 65%         | ** |

Table 2: Some results of the doll's house illumination test (see Duit, 1969)  
300 students, grades 5 and 6, 150 each board  
\* differences of percentage are <2%  
\*\* {significant according to t-test level} <1%

Many students succeeded in connecting one bulb to the battery. But to connect two bulbs (A and B) in parallel was too difficult for most students. The influence of the different geometrical structures of boards I and II is particularly marked, especially with regard to the correct use of the switches. In board I (see fig. 4), for instance, many students connected the switches in parallel to the screws  $D_1$  and  $D_2$ , i.e. in parallel to the battery. The bulbs were also connected in parallel to the switches, hence also in parallel to the battery. Although the battery became warm when the bulbs were not glowing (students learned that this is an indicator of a short circuit) and although all bulbs could be turned on and off with both switches, most students were unable to find the correct setup.

In board II almost no switches were connected in parallel to the screws  $D_1$  and  $D_2$ . But here more students than in board I connected the bulbs A and B in series and not in parallel.

#### 5. Summary

The instruction unit on the simple electric circuit for grades 5 and 6 of the IPN Physics Curriculum focusses on operating rules, i.e. an rules which should enable students to build up circuits. These operating rules are based on connecting conditions which may be summarised by the topological

structure of the electric circuit as outlined in fig. 1. A flow model of current is also introduced in the unit, but is given only little attention in the very beginning. The results of a paper and pencil test point out that most students gain a representation of the topological structure of the electric circuit which allows them to solve test problems successfully. Most students, for instance, are able to predict whether a circuit printed in the test manual will function or not and to draw correct connections between sources and consumers printed in the test manuals (see 4.1.). But many students have difficulties in recognising the structure of the electric circuit in a piece of everyday equipment, namely in an electric torch (see 4.4.). Furthermore, many students have severe difficulties in applying this structure when building up somewhat complex circuits. The geometrical structure of the equipment used in a practical test appeared to be of greater influence on students' actions than the representation of the electric circuit gained during instruction (see 4.5.). Hence students representations of the topological structure of the electric circuit (see fig. 1) appear to be less well established than one would think when taking only the results of the paper and pencil test into account.

Some remarks on the use of current flow models will conclude this paper. Our findings point out that such a model does not aid an understanding of connecting conditions in the very beginning (see 4.2.). It is notable that significant correlations between tasks concerning connecting conditions and tasks concerning the flow model formed mainly after the instruction unit.

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## Semantic Structures Describing the Electric Circuit Before and After Instruction

Christoph v. Rhöneck and Bruno Völker

### 1. Introduction

The representations of students' concepts describing the electric circuit is of importance because structured concepts may influence the perception and description of processes, the handling of electrical devices and the assimilation of physical concepts. These aspects were studied by different methods and led to complementary results.

Tiberghien and Delacôte, 1976, used a manipulatory analysis of very simple circuits and described the representation of the phenomena. As their most essential result Tiberghien and Delacôte emphasized that the battery acts on the bulb in a linear causal effect. Similar results were obtained by Osborne, 1983, and Andersson, 1980.

The semantic information of the more or less distinctive students' concepts which were used to describe electric phenomena before instruction was studied in Germany. The outcomes of these studies may be interpreted in different ways. Maichle, 1981, analyzed the representations as semantic networks on the basis of network theory (Norman et al., 1975). In this study the students' descriptions of the processes in a circuit will be related to the energy view as it is used in physics. In a first step the processes are described concisely. Afterwards empirical results will be reported and the relation to the description in physics will be drawn.

### 2. Comment on the description of the electric circuit in physics

The electric circuit may be explained as a system where energy is transformed or as a system where voltages are measured and currents flow. In the energy view

the battery is the place where energy is stored and where it is transformed from chemical into electrical energy. From here the energy flows to the electrical appliance.

The second way of looking at the electric circuit uses the concepts of potential difference (p. d.) or voltage (V), current (i), and resistance (R). The two views of the circuit are connected with each other in the following way. The energy flow  $dE/dt$  into the resistor is given by the product  $V \cdot i$ , which means current and voltage determine the energy flow. The two flows, the energy flow and the flow of electrons, should be distinguished carefully. While the first is unidirectional the second circulates.

### 3. The semantic information of the students' concepts current, voltage and resistance, and the students' energy view

It does not surprise that the student uses the words current and voltage before instruction different from how the physicist uses them. Before instruction current is a students' concept which shows at least two features which are not included in the physical concept of current: The "current" may be stored in a battery or a wire as a static current, and the current may be consumed in a bulb or in another electrical appliance (Maichle, 1981, Osborne and Gilbert, 1979, Rhöneck, 1981). These aspects of the students' concept of current are easily to be understood as a result of the strong relation between current and energy. Some students describe current as "current is energy" and a high percentage of students accept a similar statement (Rhöneck, 1981). In addition, nearly 50% of a sample of German students (grade 6) quoted the word current when confronted with the word energy and when asked for their associations (Duit, 1982).

Taking the hypothesis of a strong relation between current and energy for granted the question arises whether

or not students' concepts of resistance and voltage exist. Most of the students seem to relate a bulb to a consumption and not to a hindrance of the current. Also, to a majority of students the word resistance in connection with a bulb is not familiar (Maichle, 1981, Rhöneck, 1981). The scientific correct conception that the current has the same value before and after the bulb is held by a small minority of students before instruction (Osborne, 1983).

The word voltage is known to many students in the early years of secondary school. Especially, voltage seems to be related to the current. The circumscription "voltage is the force or the strength of the electric current" is not used infrequently and the student often keeps this definition when the voltage has to be predicted across the bare wire or the switch in a circuit (Rhöneck, 1981, Maichle, 1981).

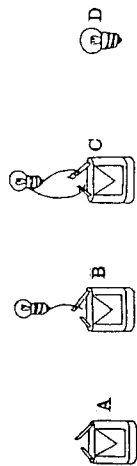
A structure becomes visible when this semantic information of current, voltage and resistance is combined. Usually the students' view of the electric circuit is influenced by the energy view even when using the words current and voltage. In this so-called students' energy view current is a first order concept. The students' concept of current is marked by features which are similar to the aspects of storage, transportation and transformation of energy in physics even though the aspect of conservation may be missing. The voltage is a second order concept and connected to the current. Preconceptions of a resistor as a hindrance of the current generally do not exist.

This short description of the expected relations between the different students' concepts and an underlying basic idea of a students' energy view of the electric circuit may facilitate the understanding of the test items which are comprised in the following test.

### 4. The test items and the concept mapping before instruction

The tasks of the test are presented in fig.1. The first task was utilized by Maichle, 1981, and the second

- ① Look at the four arrangements A, B, C and D.



Read each of the sentences below and put a tick in the box if you think the sentence is true. If you don't know tick off the corresponding box.

|                                          | A                        | B                        | C                        | D                        | I don't know             |
|------------------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 1. The bulb shines in figure:            | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 2. An electric current exists in figure: | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 3. An electric voltage exists in figure: | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

- ② Considering figure 2 there is no bulb in the lamp-socket. The switch is on.

lamp-socket



There is an electric current in the wire leading to the lamp-socket. Tick if true.

|  | true                     | false                    | I don't know             |
|--|--------------------------|--------------------------|--------------------------|
|  | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

Fig. 1. Tasks to assess the semantic structure

- ③ The bulb is connected with the battery. The bulb shines. Decide in each of the following sentences!
- |                                                               | true                     | false                    | I don't know             |
|---------------------------------------------------------------|--------------------------|--------------------------|--------------------------|
| 1. The bulb consumes the electric current.                    | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 2. The bulb drives the electric current.                      | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 3. The bulb hinders the electric current.                     | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 4. The bulb takes part of the energy of the electric current. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 5. The bulb is a resistor.                                    | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

- ④ Here you find sentences which are related to the electric current and the electric voltage. Put a tick in the corresponding box if you think the sentence is true, false or you don't know.

|                                                                           | true                     | false                    | I don't know             |
|---------------------------------------------------------------------------|--------------------------|--------------------------|--------------------------|
| 1.a. The electric voltage and the electric current occur always together. | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 1.b. The electric voltage may occur without an electric current.          | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 1.c. The electric current may occur without an electric voltage.          | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 2.a. The electric current is energy.                                      | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
| 2.b. The electric voltage is energy.                                      | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

task by Osborne and Gilbert, 1979. Both tasks allow the investigation of the static and kinematic aspects of the students' concept of current. Task 1 gives additional information about the meaning of voltage. Task 3 is related to the question whether the bulb is perceived as a hindrance and resistance or as a consumer of the electric current. The last task is dedicated to the relations between current and voltage on one side and the connection between current and energy on the other side.

The concept mapping serves as a clear representation of the different results and supports an analysis of the students' view of the electric circuit. The purpose of this analysis is to separate the students' energy view from a correct view of the circuit. Of course, other tasks and better tasks may be chosen to describe the so-called students' energy view, and other views of the circuit may be isolated.

In the concept mapping the three concepts resistance, current and voltage are delineated on one level whereas the energy concept which combines some aspects of the students' energy view is placed on another level. To begin with, the relations compatible with the students' energy view are described. These relations do not exist in physics. "The bulb consumes the current" indicates a connection between the bulb and the students' energy view whereas in physics the current  $i$  is constant everywhere in the circuit and cannot be consumed. The phrase "voltage and current occur always together" indicates a too strong connection between current and voltage while "the electric voltage may occur without the electric current" describes correctly the situation where a battery is not connected to an electrical appliance. "Current is energy" may be understood as an explanation of current in the students' energy view. All these statements are presented in the concept mapping. When a student ticks off A, B and C in line 2 of task 1 and marks task 2 as true he starts from a static electric current in the batteries and in the wires. This static electric current has an equivalent in

the stored energy in the students' energy view but not in the scientific concept of current. Another incorrect strategy is to tick off current and voltage in the same way. These two distinctive strategies are represented in the concept mapping by wavy lines.

For a group of students, when all information is combined in one figure a synopsis of the two views is obtained. Fig. 2 presents the concept mapping of a group of students from a Gymnasium (grammar-school) in Germany directly before instruction.

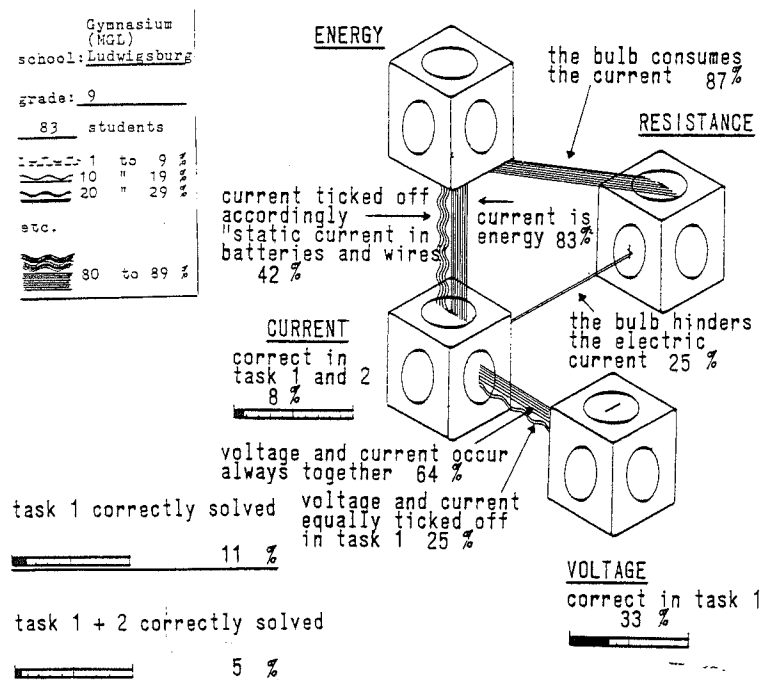


Fig. 2 Concept mapping before instruction

The figure shows a predominancy of relations which are

not included in a scientific correct view of the electric circuit. However, the agreement with a single "false" statement or a certain incorrect strategy is not 100 per cent and has no dogmatic quality. This partial vagueness of the items may be explained by broad students' concepts which do not exclude the correct semantic structures. In any case, relations are recorded before instructions which do not harmonize with the semantic structures in physics.

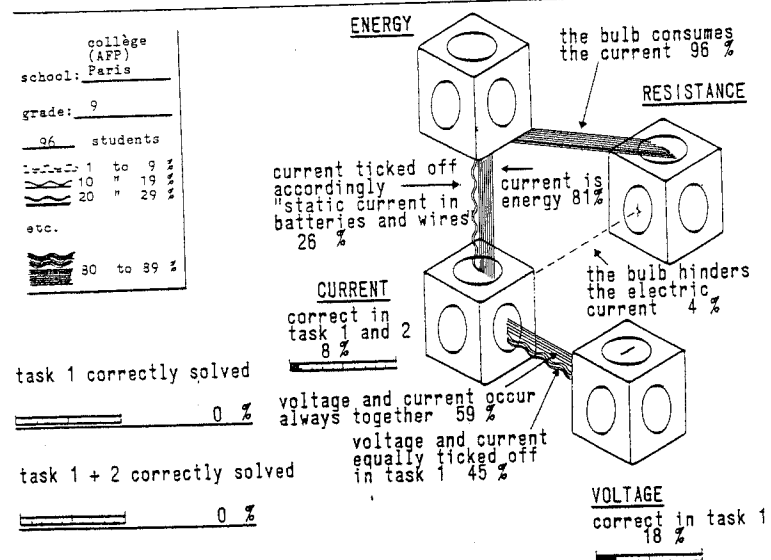
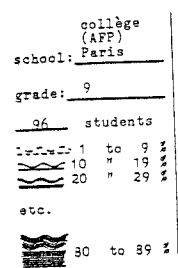
##### 5. The concept mapping after instruction

The semantic structures obtained with the same methods after a first period of instruction usually do not show the expected changes. The tasks presented to the students contained some additional questions in task 1, 2 and 4 which cannot be translated because there is no distinction between current and  $i = dq/dt$  in English as it is in the French and German language ( $i = l'intensité\ du\ courant$ ,  $i = Stromstärke$ ). In the following, the restricted results are discussed where only the term current is included.

The concept mapping of the results of selected groups is presented in fig. 3 and 4. Figure 3 shows the outcomes of a school in Paris (grade 9) several month after instruction and the results of a Gymnasium (grade 9) in Ludwigsburg 4 weeks after instruction. In both cases a distinction between an energy view and the  $V/i/R$  view of the circuit was not explicitly taught. When the different views are not discussed they generally seem to resist the period of instruction.

Fig. 4 shows the concept mapping of two groups (Realschule/technical school) which were especially taught. The first of these groups was instructed with a particular emphasis on the concept of voltage. This objective was accomplished to a sufficient extent, as additional tasks could show, but the mapping did not reflect a change in the view of the electric circuit. Discussions on the level of concepts seems not to be a promising strategy when the change of the view is intended. Especially unsatisfactory was the strong relation between current and voltage which





Realschule  
(RHH)  
school: Ludwigsburg

grade: 9

47 students

|           |    |    |   |
|-----------|----|----|---|
| <u>1</u>  | to | 9  | % |
| <u>10</u> | "  | 19 | % |
| <u>20</u> | "  | 29 | % |

etc.

|           |    |    |   |
|-----------|----|----|---|
| <u>30</u> | to | 39 | % |
|-----------|----|----|---|

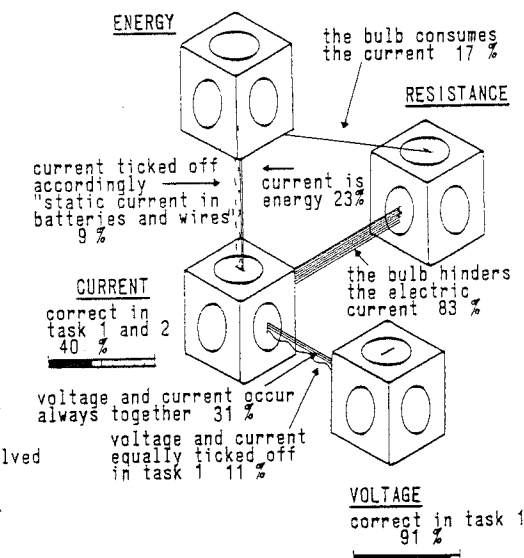
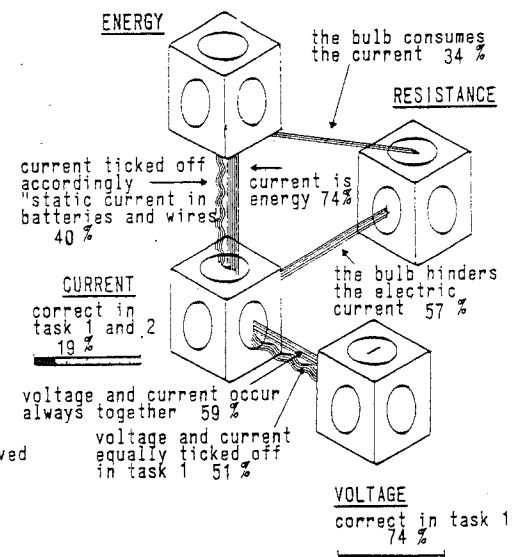
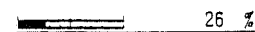
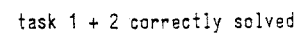
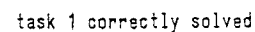
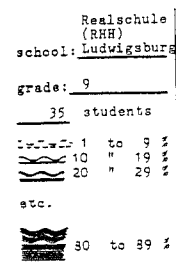
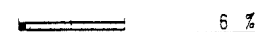


Fig. 4. Concept mapping after instruction

was not weakened (v.fig.4a). The new concept of voltage seems to be embodied in the students' energy view of the circuit. In this regard the results of fig.4.b are much better. Here the energy view and the  $V/i/R$  view were explicitly discussed and the mapping indicates some changes directly after instruction in the correct direction.

The concept mapping of the first attempt to distinguish between the different views in a Gymnasium records good results directly after instruction and rather good results four month later.

The results discussed so far indicate the students' difficulties to differentiate the energy view and the  $V/i/R$  view of the electric circuit as they are used in physics. These views should be taught explicitly and in multiple situations during instruction (Härtel, 1982). The teacher should be aware of the necessity to present information on single concepts and their relations as well as on mental structures and views.

In fig. 5 the level of concepts contrasts with the level of structures. The arrows indicates the transitions between the different elements of a teaching unit underlying the results presented in fig. 4 b. A detailed discussion of fig. 5 exceeds the purpose of this paper.

The discussion of the views of the circuit is a very difficult task for the teacher. But this task may become easier when the semantic structures which disturb the process of learning are identified. A certain change of the very broad views before instruction seem to be possible when the different views and the various concepts are described appropriately. Perhaps, the increase of an understanding of the simple electric circuit leads to a better performance when more complicated circuits (Closset, 1983, Shipstone, 1982), circuit diagrams (Fredette and Clement, 1980, Joshua, 1982) and more complex problems (Riley et al., 1981, Caillot and Chalouhi, 1983) are presented.

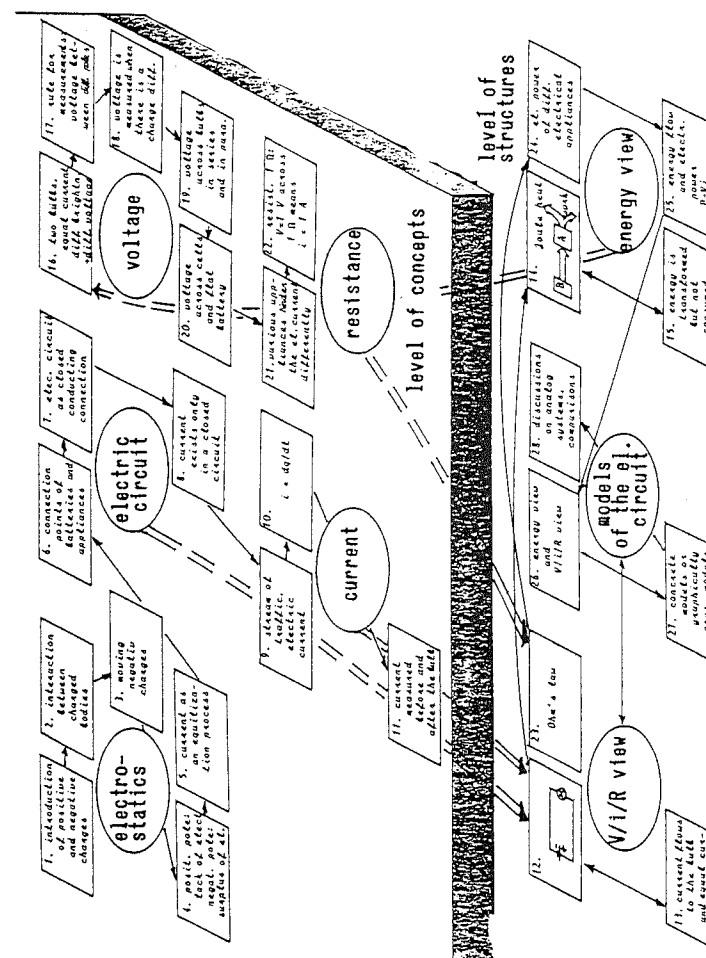


Fig. 5. Teaching sequence on the level of concepts and on the level of structures

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### CAUSAL RELATIONS IN ELECTRIC CIRCUITS: STUDENTS' CONCEPTS

Raphael Cohen

#### Abstract

Following a previous study which showed that students, often, analyze electric circuits incorrectly because of a "current conception", an effort was made this year in two classes (11th and 12th grade) to emphasize a "voltage conception". The results are not conclusive, but it seems that it is possible to correct students' views in this domain if one is aware of the source of their difficulties.

I had this year the opportunity to teach electricity in two classes, an eleventh grade and a twelfth grade. These classes had already been taught electricity in ninth and tenth grades, not by me. First let me summarize in a few sentences the program (1, 2) they learnt in these grades in electricity.

"Playing" with cells and bulbs, the students discovered a phenomenon called "electric current", manifesting itself by heating, showing chemical effects and magnetic effects. They found that one can reduce the magnitude of these effects by adding bulbs (in series) and increase them by adding cells (in series again). By using compass needles as primary "current meters" they have been aware of a kind of "current conservation", that was emphasized after introducing ammeters. After defining resistance (mainly as an "obstacle") they were able to state that "the main current divided at a junction in inverse proportion to the resistance of the parallel paths".

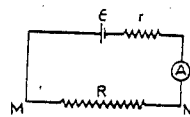
Later they defined p.d. between two points in a circuit as energy transfer per unit charge between these two points. And then they solved some problems of circuits with one source, with or without internal resistance, and a few resistors, some of them in series and others in parallel. The e.m.f. of a battery was presented as the energy given to each unit charge, and a voltmeter can measure it because  $V = Ri$ .

Now let us see what kind of confusion could be constructed in the students' minds. Energy was not known when they began the study of

electricity: on the contrary, electricity was the motto to introduce energy, by means of "the missing heat". They had no notion of mechanical energy, or work, or something equivalent. The concept of electric charge was also missing, and in fact it was something very abstract like  $q = it$ . Some students have heard about electrons that move in metals, but the charge they were taught about was positive by definition! Being probably confused both about energy and electric charge, they were then told that p.d. is the ratio of these two very abstract quantities. How could they have any representation of p.d. and its role in producing the electric current? In fact, for a few months, they were never induced to think why is charge moving in an electric circuit. (Possibly they were never asked this "rude" question). They only knew that in a closed circuit there is a current, if there is a source. Isn't it natural for a student with the previously described experience, to conclude that the source is a source of current? Isn't it natural to consider the p.d. as some kind of attribute of the electric current? Isn't it natural to look upon p.d. as what is shown by the voltmeter, whatever it means? And then concluding that p.d. derives from current, and does not exist without it? Naturally, the solution of simple problems by the students does not involve a deep understanding of "what is going on", but rather a manipulation of a few formulas in a technical manner.

When I started to teach the electricity course this year in these two classes, I tested the students on some of the questions that were included in our previous work (2), not the difficult but the obvious ones. Here are the questions:

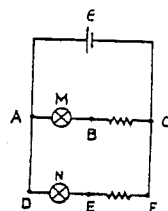
1. In the circuit given in the figure, the reading of the ammeter is  $I$ . An additional resistance  $R'$  is connected, in parallel with  $R$ , between M and N.



What happens to the reading of the Ammeter?

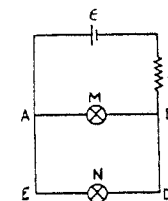
Does the p.d. between M and N changes? If so, how?

2. The Voltage Source  $E$  in the figure has no internal resistance. Both bulbs M and N are lit. N is removed from its socket.

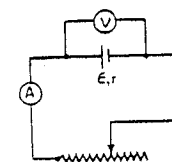


- a) What happens to the light of M?  
b) What is now the p.d. between D and E?

3. Same question as 2.



4. In the circuit drawn in the figure, a voltmeter is connected to the terminal of a battery with an e.m.f.  $E$  and internal resistance  $r$ . The ammeter has no internal resistance, and it indicates a current  $I$ . The voltmeter indicates a voltage  $V$ . The resistance of the rheostat is reduced to zero. What happens to the readings of the two meters?



The pattern of answers was exactly the same as in our previous work. In the first question, most of the students thought that the reading of the ammeter will not change, because "the main current will now divide into the two resistors". Most of those who gave this answer thought also that the p.d. will not change, but a few sophisticated ones said that since the equivalent resistance between M and N is now reduced, so is the p.d. A few of the students thought that the reading of the ammeter will increase "because the p.d. between M and N does not change". Only one student could think about the two quantities as changing simultaneously.

The difference between questions 2 and 3 is only in the arrangement of the circuit elements, and is not clear at all to the students. In fact, no one gave different answers to the two questions: all of them thought that the p.d. is zero when the bulb is removed, and M will light more brightly. It is evident from these answers that the students assumed that M "receives" now all the current that was before in N.

The fourth question showed clearly the reluctance of most students to admit that voltage and current can change in opposite directions. Most of them stated first that the current will increase because resistance decreases, and then  $V$  must also increase. A few seemed puzzled by the fact that there is a high voltage on a zero resistance. Some of them even introduced a resistance to the ammeter (although it was explicitly given in the question that it has no resistance), in order

to justify the increase in voltage.

In conclusion, the trends were very clear: "At the beginning there was current". The reasoning throughout is "current minded", and a p.d. is a consequence of current and varies always in the same way. In particular, if there is no current, there is no p.d. Through students answers to oral questions, it was evident that they had no idea what kind of mechanism induces current in a closed circuit.

In view of all this, I decided to try to change the attitude of students from "current minded" to "voltage minded". This, I knew, would be a difficult job because it does not seem to be a natural mode of thinking. (I had a very interesting experience last year: When I presented our work to an audience of teachers and researchers in physics teaching at the Paris University, and showed the questions I gave to my students without giving immediate answers, I got very often from the audience the same kind of wrong answers and wrong reasoning manifested by the students).

The students of the two classes were already after a course in mechanics, and thus it was possible to make a good use of the concept of potential energy and work. They were also more able to grasp models, after using this notion in optics, and their mathematics was rather developed. The first step was to get them to understand the relationship between potential difference and current by using an hydrostatic model. Relating potential energy and hydrostatic pressure, comparing it with "electric pressure", the model allows us to see that there is a net force on each particle which can move in a conductor if there is a p.d. at its ends. A byproduct of this model is understanding the propagation of the influence of the p.d. by a wave (e.m. wave) in the same way that hydrostatic pressure is propagated by a wave whose velocity is great in comparison with the velocity of the liquid.

I am not going to give all the details of my teaching, but all the discussions of any relevant problem were always emphasizing voltage distribution in the circuit, taking in account the additivity of voltages around a closed path, and the constancy of the voltage of sources. The current often appeared as a secondary concept.

As an example, let us look at a meter. It is commonly said, and it is true in practice, that a voltmeter is an ammeter with a resistor in

series. I took deliberately an opposite view: Any meter is a voltmeter that measures the p.d. on itself. Each meter is characterized by its maximum voltage drop, and may measure voltages in parallel connection, provided the voltage it has to measure is within its range, that can be changed by changing its resistance. This, by the way, gives a very convenient way of finding the value of a shunt for a given range of current measuring: The shunt must be such, that the p.d. on it, produced by the difference between the maximum current of the range and the current through the meter itself, has to be equal to the maximum p.d. of the meter.

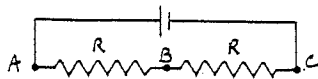
As another example, the expression "the main current divides..." was forbidden. Instead, the students were urged to say "the current before or after a junction is the sum of the currents in the parallel paths". The parallel connection to a source was emphasized, and the notion of a resistor as a "consumer" was developed.

As a final example, I would like to report on a demonstration I showed to the students: A coil of 500 turns ( $R \sim 5\Omega$ ) is connected first to a milliammeter, and then to a microammeter. In the two cases I move a bar magnet into the coil at the same speed, and, Miracle, the milliammeter gives a much bigger deflection than the microammeter (about twice the deflection). At first glance, this looks paradoxal: All the students believed that the deflection of the milliammeter should have been much smaller; some even thought that the deflection of the milliammeter would be too small to be observed. Again the source of the paradox lies in the belief that there is an "induced current". The analysis of the experiment brought the students to the unavoidable conclusion that what is induced is not a current, but an e.m.f., and the current is only the consequence of having closed the circuit with this e.m.f. The two meters measured both e.m.f., and it so happened that the milliammeter was more voltage sensitive than the microammeter.

For about four weeks, I struggled with my students to overcome the "current conception", and use a "voltage conception" in analysing electric circuits. In the final exam I gave my students the following question, which happened to appear later this year in the general matriculation exam:

Two equal resistors  $R$  are connected in series to a source without internal resistance, whose e.m.f. is 12 V.

A voltmeter with a resistance of  $50000\ \Omega$ , is connected first between A and B, then between B and C, and finally between A and C. What will be the readings of the voltmeter in the two cases: 1)  $R = 5\ \Omega$  ii)  $R = 50000\ \Omega$ . Explain the case of  $V_{AB} + V_{BC} \neq V_{AC}$ .



I was one of the teachers who checked the matriculation exam. I was not surprised to see the enormous amount of calculations most students did, even to find  $V_{AC}$ . Almost all of them wrote long equations for finding the equivalent resistance in all cases for all voltages. Most of the explanations for  $V_{AC}$  being different of the sum of the two voltages, were along the following line: "in the second case the current through the voltmeter is not negligible, and this accounts for the inaccuracy of the measurement".

To my students it was clear that in the two cases  $V_{AC} = 12\text{V}$  without any calculation. It was also clear to them that in the first case ( $R = 5\ \Omega$ ) the voltmeter does not introduce any significant difference, and the voltages are equal. In the second case ( $R = 50000\ \Omega$ ) some of my students made also lengthy calculations. But I was pleased to see that many of them solved the problem very simply, by saying that since the connection of the voltmeter reduces the equivalent resistance to half the value of the other resistance, and then to one third of the total resistance, the reading of the voltmeter would be one third of the total voltage, e.g. 4V on the voltmeter the voltage on the other resistor was 8V, and thus the sum is always 12V.

In conclusion, I cannot be sure that most of my students have really changed their representation profoundly. However, they acted in class as if they did. Very often a student would begin the analysis of a circuit with currents, but most of the time he would be able to stop, and realise that it is better to use voltage as cause of current.

The only way to reinforce that trend is to practice much more than we usually have the time to do it in physics classes. It has been detected that among students of vocational schools for electricity and electronics, this kind of voltage analysis begins to be natural, due to their wider experience and practice.

A last commentary is necessary: In our previous work we found that most students, independent of their previous curriculum, failed in the analysis of the circuits. This indicates that not only students of Rehovot program have problems of representation. Almost all students are exposed, at some time, to some early program of electricity that does not emphasize causal relations between voltage and current.

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THE DIFFERENTIATION BETWEEN CONNECTIONS IN SERIES AND IN PARALLEL FROM  
COGNITIVE MAPPING; IMPLICATIONS FOR TEACHING

Hans F. van Aalst \*)

1. THE QUESTION

In this paper, I would like to pose the following question:  
"Why is it that most textbooks for secondary education treat serial and parallel connections of resistors bracketed together within one chapter?"  
Would not be it advantageous to treat each of these arrangements with much more care and independent of each other?

2. WHY THE QUESTION? Some research-outcomes

The question posed did come to my mind several years ago. The PLON-project<sup>1)</sup> - from which I was the coordinator then - had developed a trial-unit called "Electricity and Heating". The unit was for use with 14 - 15 years old pupils. Evaluative research was conducted during the trial to analyse its quality.

Use was being made of: - association-tests<sup>2)</sup>  
- concept-pairing-tests<sup>3)</sup>  
- pupil- and teacher-questionnaires;  
- pupil-performance-tests,

and these were being used before and after the trial to find out what pupils already thought before going through this unit and in what sense the learning had substantial effects.

Some of the results (after teaching) were the following (Wierstra et al, 1979):

- "serial-connections" is associated mainly with "closed loop of current" and - in higher order - with "resistance";
- "parallel-connections" is associated with "use of electricity" and only in third order with the cluster "resistance - serial-connections - closed loop of current";
- there is very little association between series- and parallel-connections, although both had been taught in relation to each other.

Also it was found that there was a tight and coherent relation between "electric-current" and "electrical energy", and - perhaps closely related to this, a rather large percentage of the students (about 60%) did hold the

idea that "current" is "used" when passing a component in a series-circuit, thus: current before passing has a higher value than after passing. "Current" and "voltage" are closely associated, but not very coherently. "Use of Energy" has mainly technological and social connotations (kwh-meter, money, waste). "Voltage" is mainly associated with High-Tension and danger, and with short-circuiting. The notions which physicists would connect to "voltage" are given to "current" and "electrical energy".

It was decided to discuss the results of the evaluation-study together with an advisory board of the project. In this board several experienced physics teachers teachers-trainers, curriculum-development-experts, science inspectors and others came together from time to time to discuss the planning of the PLON-project.

Not so much had been published in that time about pupils' frameworks, pre-conceptions etc., but experienced teachers were certainly well aware that these existed. This might explain why out of the range of results the main point discussed was the finding that the notions of serial- and parallel-connections were so far apart in students conceptual structures.

The general feeling was, that this apartness was a serious shortcoming of the unit. "Series" and "parallel" should be two kinds of a pair. But should it really? I remember my own position being not so sure.

### 3. A MATTER OF OBJECTIVES

It was one or two years later that I deliberately took the point of view that a certain separation between series and parallel connections could be valid, and should not be seen as a shortcoming per se.

Let me try to explain this.

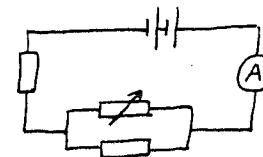
A traditional aim of teaching electricity is to understand abstract concepts such as "voltage", "potential difference", "current" and "resistance". Understanding means that pupils can solve problems, using these concepts.

If you want to test this understanding, you offer different problems.

Problems should not be trivial and not too complex. A problem is a question about a situation. Situations offered should be equal in terms of physics, i.e. the same concepts should apply.

Since there is no conceptual differentiation (the same concepts apply), adequate complexity of problems is determined by the complexity of the

situation. In practice - for example in examinations - one takes circuits such as the following:



Apparently, current practice reveals the idea that understanding of the concepts of electricity can not be demonstrated adequately in simple series- and parallel-circuits, but only in circuits which combine both connections, such as the one above.

Consequently the teaching of simple series- and parallel-circuits is only an intermediate step to their combination.

The argument until now has been derived from one point of view: children in secondary education learn the concepts of electricity and demonstrate their ability in applying these to non-trivial situations. One could call this a model of learning-outcomes: the "concept-application"-model. Is this model really valid? I would argue that its value is really very limited, for a class of students. It is an expert-model. Analysis of childrens learning has been given evidence to me to suspect that most children do not solve problems by applying abstract concepts to a situation. In fact they compare the situation to situations earlier handled. They perceive and analyse a situation not only in conceptual terms. For example: most children connect functional properties to a situation: they try to think about something of use.

I would suggest a different model for school-learning: Children - as all people I would suspect - do not learn concepts, they learn how to deal with certain situations. The concepts actually learned, are not only abstract, but are "flavoured" with characteristics of the situations handled during the learning process. Concepts learned have a contextual component.

If one adopts the view that learners always hold a connection between concept and context, then situations used in teaching and testquestions are not longer conceptually equal, it is not longer only the situational complexity which determines the adequacy of the problem, but also the



contextual characteristics<sup>4)</sup>.

It might be that simple parallel-circuits have potentially different contextual connotations than simple series-circuits have, and they may be of relevance to physics teaching. For example: parallel-circuits may be seen as systems to distribute energy and series-circuits as systems to control potential differences.

It was (and is) my interest to specify learning-outcomes in such a way that conceptual and contextual aspects are integrated. The general idea has been adopted by the PLON-project. Unfortunately, research priorities in the project changed from electricity to other fields, and no further empirical data became available about electricity during the last few years. I can only report, how "electricity" has been fit in the PLON-curriculum and I will touch upon this later in this paper.

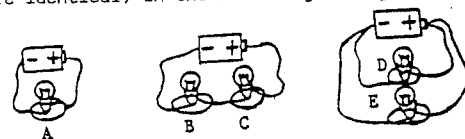
First I would like to show what I have found in literature about the differences between series- and parallel-circuits.

#### 4. EMPIRICAL EVIDENCE ON SIMPLE CIRCUITS

There is empirical evidence that pupils, after instruction, have difficulties in stating the differences between parallel- and series-circuits.

I refer - as an example - to L. Mc. Dermotts study (1984):

"Predict the relative brightness of the lightbulbs (all the bulbs and all the batteries are identical) in the following arrangements:



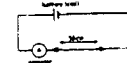
About 25-30% of college-students who had completed the study in electricity in standard introductory physics courses could give the right answer. Only one out of 23 students was able to explain her answer correctly.

From this study and several others, it could be concluded that students who got elementary training have difficulties in qualitatively interpreting the differences between these three very simple circuits. This was the case, even although many were well able to use calculations correctly.

Analysis of answers revealed that one of the reasons is that students might be correct in one circuit, and apply this to another.

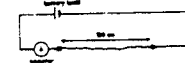
Gott analysed APU-data and found that 33% of 15 years old students in Britain gave correct responses in question (a) below, 18% gave correct responses to question (b), but only 4% gave correct responses to both questions. 33% saw no difference in the effects the different arrangements would have on the current flow (Gott, 1984, p. 34).

A pupil connected a 50 cm length of resistance wire between two crocodile clips in the circuit. He noted the current reading on the ammeter.



The reading on the ammeter was 2 A.

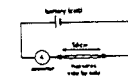
a) What would the current in the circuit be if he used a 100 cm length of the same wire?



Ammeter reading.

Give the reason for your answer.

b) What would the current in the circuit be if he used two 50 cm lengths of the same wire side by side?



Ammeter reading

Give the reason for your answer.

So, one might conclude that physics-teaching does not seem to be quite adequate here: simple circuits are not well understood. One could expect that the results with combined circuits are better, because considerable time is being spent to teach problems about such circuits. Unfortunately, results with combined circuits are often worse, and many difficulties are exactly the same as the ones already there in more simple circuits, as can be seen in the following paragraphs.

#### 5. EMPIRICAL EVIDENCE OF CONCEPTUAL DIFFICULTIES IN ELECTRICITY

In table I, I listed conceptual difficulties which children have in solving problems with combined-, series-, parallel- and mono-circuits. The first being reported in the very most cases.

I do not give detailed references, they can be found in the other contributions to this seminar, or in the list of references in the proceedings of the first international workshop on Research in Physics Education (e.g. Tiberghien 1984, Von Rhöneck 1984). Nor does this paper allow me to illustrate each point. But the reader can check the conclusion:

Table I clearly reveals, that many conceptual difficulties in solving problems in combined-circuits are also there in series- and parallel-circuits and even in mono-circuits. A few are typical for the circuit specified.

In general, most difficulties are very common, even with students who are considered to be "good" physics-students.

TABLE I

CONCEPTUAL DIFFICULTIES IN COMBINED-, SERIES-, PARALLEL- AND MONO-CIRCUITS

|                                                                                                                        | C | P                                | S                                                                 | M |
|------------------------------------------------------------------------------------------------------------------------|---|----------------------------------|-------------------------------------------------------------------|---|
| 1. Notion of "something"(electricity, current, power, energy etc.)<br>Language/insecure use of words                   | X | X                                | X                                                                 | X |
| 2. "Current" as a prime idea, not voltage                                                                              | X | X                                | X                                                                 | X |
| 3. No current means no voltage                                                                                         | X |                                  | X                                                                 |   |
| 4. Battery supplies constant current instead of voltage                                                                | X | X                                | X                                                                 | ? |
| 5. Current is "used up" in sequence of components in the circuit                                                       | X |                                  | X                                                                 |   |
| 6. Equal share of <u>current</u> over components in circuit                                                            | X | X<br>after<br>teaching<br>of S!) | X<br>after<br>teaching<br>of V)                                   |   |
| 7. Variation of potential differences cannot happen if voltage of battery is constant                                  |   |                                  | X                                                                 |   |
| 8. Local reasoning without taking into account global constraints                                                      | X | X                                | X                                                                 |   |
| 9. Inability to apply formalism to actual circuits                                                                     | X | X                                | X                                                                 | ? |
| 10. Little transfer to new situations which are analogous with prototype                                               | X | X                                | X<br>e.g. If one takes 5<br>components in series<br>instead of 2. |   |
| 11. Interference of S- and P-ideas                                                                                     | X | X                                | X                                                                 |   |
| 12. Incorrect use of meters                                                                                            | X | X                                | X<br>esp. V-meters after<br>teaching of C-circuits                | X |
| 12a Uncertainty about function of bulbs<br>Do they indicate current? Voltage?<br>Are they "resistors" or "conductors"? | X | X                                | X                                                                 |   |
| 13. $I \uparrow$ means $R \uparrow$ v.v.                                                                               |   |                                  | X                                                                 | ? |
| 14. More R's means $I \downarrow$ ( $R_{tot}$ in P-circuit is artefact)                                                |   | X                                |                                                                   |   |
| 15. Power distribution                                                                                                 | ? |                                  | X                                                                 | ? |

However: Most of the research reported is based on the "concept-application"-model, to which I referred above. Virtually no results can be found about contextual factors which determine cases in which pupils could solve problems correctly. The research reports that not all students are experts, it does not report what they can do nevertheless.

#### 6. EMPIRICAL EVIDENCE OF NON-CONCEPTUAL DIFFICULTIES

I listed the difficulties reported in paragraph 5 as conceptual. Of course one cannot really make the distinction between conceptual and non-conceptual difficulties. Indeed the numbers 8-10 in table I might well represent strategic difficulties instead of conceptual ones. Some authors (e.g. Shipstone 1983, Closset 1983) make the case that sequential reasoning (table I, nr. 15) is in fact underlying many of the other conceptual misconceptions mentioned.

But there are more general difficulties which I call, just for the purpose of this paper non-conceptual. Table II lists these difficulties. I suspect that many of the reported conceptual difficulties are in fact a result of these non-conceptual ones. For this reason, and because not so much can be found about these in literature, I will elaborate on some of these a little. All of them apply to each of the circuits mentioned, but with different intensity.

TABLE II

NON CONCEPTUAL DIFFICULTIES IN SOLVING ELECTRICITY-PROBLEMS

- a) Inadequate (use of) analogies
- b) Inability to handle simultaneous change of variables
- c) Conceptual and perceptual problems with diagrams
- d) Inability to solve (context-free) non-functional problems
- e) Fear for qualitative reasoning (perceived lack of accuracy)

ad. a): Use of analogies

Gentner and Gentner (1981) reported that out of 36 highschool- and college-students, fairly naive about physics, 15 used consistently a current-analogy to explain simple electric circuits; 21 were inconsistent or did not use a current-analogy.

What is interesting from this study is that two different current-analogies have been detected: one being in terms of traffic: the moving-crowd-model and one being in terms of flow of water.

Gentner and Gentner show that the moving-crowd-model is more appropriate for understanding serial- and parallel-combinations of resistors, than the water-flow-model (this model is more appropriate however for understanding combinations of batteries).

Students who were taught the moving-crowd analogy could differentiate parallel- versus serial resistor configurations more accurately than students who had learned the water-model. Also, between students who were not being taught in any model, but reported to use one of the models, the moving-crowd-model yielded better results for resistor-configurations.

Because analogies used in thinking have a substantial role in concept-formation, there is room for the hypothesis that some problems children have in simple circuit-tasks stem from the use of an inappropriate analogy, either be it because of previous teaching or from spontaneous use.

Von Rhöneck stresses this point also. (1984).

On the other hand, my own observations tend to the conclusion that one should be careful to connect one analogy to one group of situations. Sometimes children use - rather idiosyncratically - several analogies in the same time to explain one situation.

ad. b): Simultaneous change of variables

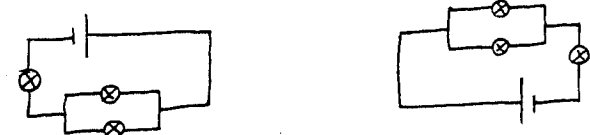
This is very well known, and there is no need to explain this here.

ad. c): Reading diagrams

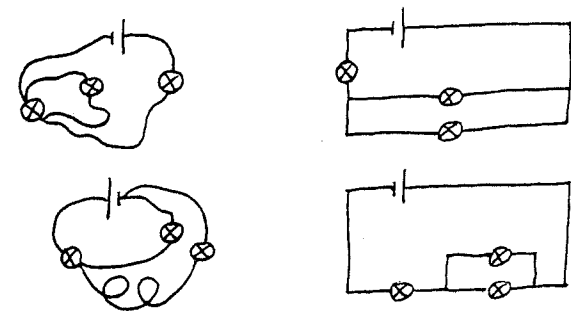
The problem of reading diagrams is often overlooked. Difficulties in this field are at least two-fold: perceptual and conceptual.

The perceptual problem is clearly stated in a paper of Elsa Feher (Feher, 1983). She found that almost one quarter (!) of a class of college-students who had no previous exposure to electricity-teaching, had perceptual problems: poor spatial visualisation, problems with actual manipulation of whole configurations. Students who had predicted correctly what would happen in a certain circuit, did not recognize it as being the same entity when it was rotated.

An example is given on the next page:



This is different from the conceptual problem of seeing several types of circuits as equivalent from the operational point of view, not equal: equivalent. For example look at the following set-ups:



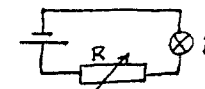
Is it really obvious that these are equivalent? Why do coils in wires not matter in this case? They do matter in the work on magnetism!

Different examples are given by Caillot (this seminar). Joshua (1983) suggests relations between perceptive and conceptual factors: most circuit-drawings seem to presuppose a fluid-model, on the other hand physically different circuits may be drawn very much alike, and this induces faults.

ad. d): The lack of functional evidence

Consider the following two questions:

Question 1:



What happens to the current if  $R$  is increased?

Question 2:



Your lamp is too bright. Would a resistor in series help? Try and explain.

I would expect question 1 to have a high proportion of wrong answers, because no reason for increasing  $R$  is given. I have argued elsewhere (Van Aalst, 1982) that children often use functional reasoning before causal reasoning. They must have a feeling of the functional "why". Question 1 has a hidden functional "why": I want to know about your concept of current.

The point has been made in a different way by Johsua (1982); he noticed that students, saying that a current was passing through  $R$  in the circuit given:



did reason so, just because  $R$  was there. And because  $R$  was there, it could not be without utility, so some current should pass through it.

#### ad. e): The fear for qualitative reasoning

Students seem to fear qualitative reasoning as a way of problem-solving, there is a tendency to approach problems technically, and this tendency is stronger as problems are more complicated.

E.g. Cohen (1983) reports about students, asked to solve more complicated problems: "About a third of the students did not try to solve these questions at all" and "Over half of the students applied various technical methods (Kirchhoff's laws or other computations), and most of them failed" and "During the interviews, we repeatedly found that students wanted to apply mathematical algorithms, write down formulae and try to analyze the situations to them through computations".

It might be that students consider exact numeric answers being the only correct ones. They lack experience to evaluate a qualitative answer; how to be sure whether it is good or wrong?

### 7. CONCLUSIONS AND IMPLICATIONS FOR TEACHING AND RESEARCH

Some conclusions out of these data are the following:

- 1) Many of the difficulties, reported about combined-circuits, are already there in simple series- and parallel-circuits;
- 2) Series- and parallel-circuits have also their own, specific problems;
- 3) There is a negative interference between conceptual ideas learned for series-circuits and those learned for parallel-circuits.

The implications for teaching seem to be the following:

- a) be more careful and slow in teaching simple series- and parallel-circuits, and perhaps teach them apart from each other, before handling combined circuits;
- b) special attention should be given to functional contexts of both series- and parallel-circuits. It should be accepted that many students do better in solving problems in specific simple contexts which have relevance to them, than they do when asked to use correctly verbal explanations about complex situations, using characteristics of abstract concepts. This is certainly not a matter of low-level-teaching. It is however a matter of specifying more context-dependent objectives.
- c) use of diagrams should be considered as a special aim, perhaps not for everyone, and it should certainly not be considered as "just a matter of easy notation";
- d) physics teaching should help students to evaluate verbal arguments, and show situations in which qualitative reasoning gives "better" answers than quantitative numbers.

The implications for research which comes out my analysis is mainly that many results reported about children's conceptions, may in fact be artefacts from the questions used. Research with carefully designed questions based on a more differentiated model of learning-outcomes than the "concept-application"-model, might be informative.

### 8. EXTRA ABOUT SEQUENCING

I have been suggesting to teach series- and parallel-circuits more apart, but did not say a thing about sequencing.

I see two approaches:

#### APPROACH I:

1. only parallel → teach energy-aspect, using kWh-meters
2. do something different
3. only parallel → differentiate between energy and current
4. do something different
5. only series → teach potential difference-distribution, stress that total current is dependent on all resistors.
6. etc.

Some authors argue against this scheme (Cohen, 1983, Shipstone, 1983). The main reasons given are that the approach inhibits later learning of voltage to be the prime concept, and also that it is nearly impossible to differentiate between current and energy without dealing with voltage.

#### APPROACH II:

1. only series connections, same accents as in I-5. Perhaps use of capacitors (Steinberg, 1983)
2. do something different
3. only parallel connections: concentrate on the fact that voltage of source is constant, and that addition of resistors increases total current
4. etc.

I do not have definite conclusions about the best approach, neither do I have any certainty that the approach we took in the PLON-project for the lower secondary age-range<sup>5)</sup> is really better than another, but it goes as follows:

#### PLON-APPROACH:

- |                  |                                                                                                                                                                                                                                                                                                                                                            |
|------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 14-15 years old: | <ol style="list-style-type: none"> <li>1. simple series-circuits, including magnetic components in the context of soundreproduction</li> <li>2. something else</li> <li>3. simple parallel-circuits, focussing on energy-measurement in the context of the home</li> <li>4. something else</li> </ol>                                                      |
| 15-16 years old: | <ol style="list-style-type: none"> <li>5. simple mono-circuits, focussing on energy-measurement, in the context of heating</li> <li>6. complex series-circuits, in the context of control-devices, such as banglar/fire-alarms</li> <li>7. simple mono-circuits, focussing on energy-measurement, in the context of mechanical energy (motors).</li> </ol> |

#### NOTES

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- 1) PLON = Physics Curriculum Development Project.  
State University of Utrecht, Lab. Vaste Stof, Postbus 80.008,  
3508 TA Utrecht, The Netherlands.
  - 2) Association-testing is the technique in which you give a word, for example "current", and ask subjects to write down all the words which come to their minds if they hear that word. We asked for associations 10 times starting with 10 words.
  - 3) Concept-pairing is a technique in which you give a pair of concepts for example: current-resistance and ask subjects to rate on a scale whether these concepts are very much related, or are not related at all. We used a scale ranking from 1 to 6, and asked for 45 pairs.
  - 4) This point is of particular interest for the construction of test-questions. See: W.E. Bijker and H.F. van Aalst: Principles for new examinations (in Dutch), NIB, Zeist, 1982.
  - 5) The approach for upper-secondary education is different. For information, see note 1.

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"Schematic diagrams, representations and type of reasoning in basic electricity"

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For some years, several studies have greatly increased understanding of the modes of reasoning students use, concerning simple electric circuits. Most studies analyse paper-pencil questionnaires including circuits represented by normalised diagrams. Sometimes, the interest is focused on real, material situations without normalised diagrams [1]. When authors examine the nature and function of electric diagrams, it is mainly with the following perspectives : psychology of work [2], research on signs and forms [3] or problem solving [4].

Studies trying to specify the relationships between electric schematisation (encoding, reading, use) and cognitive representations of students are in fact fairly rare [5] and especially those with a didactic perspective. Yet, this last question is very important when one considers the privileged role played by the diagram in electrokinetics.

#### I - General hypothesis

I.1. The first hypothesis guiding our study was that the cognitive representation of a student concerning specifically electrokinetics will be of a major influence on the reading and the use of the diagram. In fact, this hypothesis is common to all the studies presented at this workshop.

I.2. But the diagram is one signifier amongst several possible others to represent the invariants of the cognitive structure (here, for instance, the mathematical language, or, even, the natural verbal one) [6]. Each signifier, each form of language has its proper structure which will interfere with the mode of expressing the cognitive representation.

The diagram is a particular form of graphical language, in 2 dimensions, and it is probable (here lies the second hypothesis) that its peculiar rules of working are linked with the problem here studied. Beyond very general hypothesis [7], we have to consider questions such as the general symmetry of a diagram, or that of the "simplicity" of reading (which is not an easy thing to define [8]). These questions will not be developed here (for additional information, see [9]).

I.3. An electric diagram is not only a design : it is also a conceptual intermediary in physics, having consequently constitutive relations with the concepts of electrokinetics (particularly with those of current and potential). From a physical view point, a diagram must show that some electrical devices are connected and outline the topology of these connections. In the standard schematisation, these connections are attested by junction lines, conventionally considered as zero resistance.

For a physicist, a junction line between two devices signifies two things :

- current can pass through these devices (this is linked with the so-called "current reasoning"),
- the connected points are identical from an electrical point of view because they are at the same potential.

The latter convention allows us to act directly on the process of schematisation or of reading of the diagram, following a mechanism which we call "exploding of nodes". Figure n° 1 shows an example of that.

- In (a), point 2 is a node where current divides, but this is not easy to perceive.
- In (b), on the contrary, the same sharing point appears clearly.

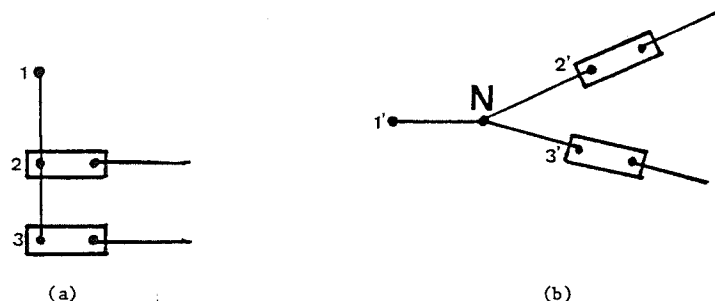


Figure 1 - The same circuit in two different configurations.

These two diagrams represent exactly the same physical situation : the zones (1,2,3) and (1',N,2',3') are equipotential ones, so this is the physical reason for the exploding of the node to get a more practical diagram. Indeed this kind of process is only possible using "potential reasoning".

Consequently, a difficulty with this notion of potential (quoted by several authors : for instance [10]) will lead to specific difficulties with the correct reading of an electric diagram. This is our third hypothesis.

## II - Fluid metaphor and current reasoning (direct current)

As many drawings (indeed an infinity) can represent the same physical situation, we come back to the questions asked at the beginning : do the forms of schematisation induce a certain kind of reasoning ? Is it a way to clarify the cognitive representations of electrokinetics ? We proposed the following exercise to try and answer these questions :

"How does the current behave between points A and B in the diagrams below ?" (see Fig. 2).

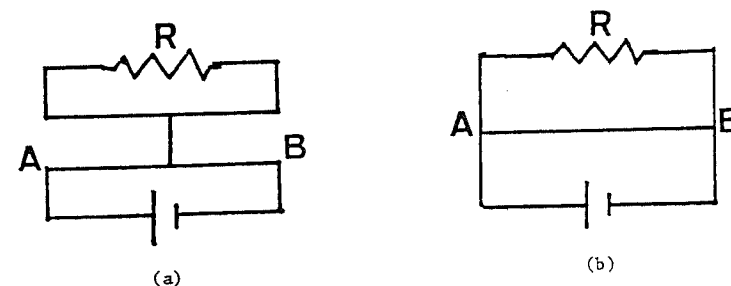


Figure 2 - Short circuit and exploding node.

In fact, no potential difference appears between A and B in each diagram : so no current goes through the resistor R. This situation shows another example of "exploding a node", and the two cases correspond to the same physical situation. However, the students answers were very different in these two cases (see tables 1, 2, 3). The typical answer which led to a correct result in (2a) was based on "current reasoning". But the same process applied to (2b) led to a wrong answer (current partition between the zero resistance wire and the resistor R). (We counted as correct answers, those which consider that a "small current" passes through the resistor). According to the students reading of the diagram, the current could pass, divide and re-combine. A very small number of them introduced a physical point of view by considering the equality of potentials between A and B.

TABLE 1  
Scientific students, first year of University

| Circuit | % correct answers | % wrong answers | % no answer | Total |
|---------|-------------------|-----------------|-------------|-------|
| (2a)    | 72                | 8               | 22          | 100   |
| (2b)    | 24                | 53              | 23          | 100   |

Distribution of answers for circuits (2a-b)

TABLE 2  
N = 96

|                                                                         |      |
|-------------------------------------------------------------------------|------|
| Current reasoning :<br>"The current has only one wire to go in and out" | 41 % |
| "There is a short circuit between A and B"                              | 41 % |

Distribution of the correct answers for circuit (2a) (extract).

TABLE 3  
N = 71

|                                                  |      |
|--------------------------------------------------|------|
| Current partition :<br>"There is a derived wire" | 77 % |
|--------------------------------------------------|------|

Distribution of the wrong answers for circuit (2b) (extract).

Fredette and Lockhead [11] asked a similar question (circuit 2b) : the majority of students considered that the current would only go through the device ; the students "used" the device since "it was in the circuit", and neglected the short circuit. We also found a minority of students using the same reasoning. But the comparison (2a) versus (2b) would show, in our opinion, that this effect is secondary with regard to the basic reasoning of students : the absolute priority is to current reasoning.

In fact, we think that the diagram is considered by the students as a figurative representation of a real piping, inside which flows a fluid, electricity. This representation is supported by what we call "the metaphor of fluid in movement". This metaphor, almost constitutively linked with "current reasoning", seems to be adopted by students beginning electrokinetics very early on. The other notion, decisive in the treatment of electric circuits, namely the potential, is missing.

### III - Alternating current

Is there a different kind of reasoning when using alternating current ? In order to verify this, we proposed the problem drawn in Fig. 3 (short-circuited condenser). The question was again : "How does the current behave between A and B ?". But now, the two diagrams are no longer equivalent. In (3a) a current will never "pass through" the capacitor. In (3b) it depends upon the frequency of the current : with increasing

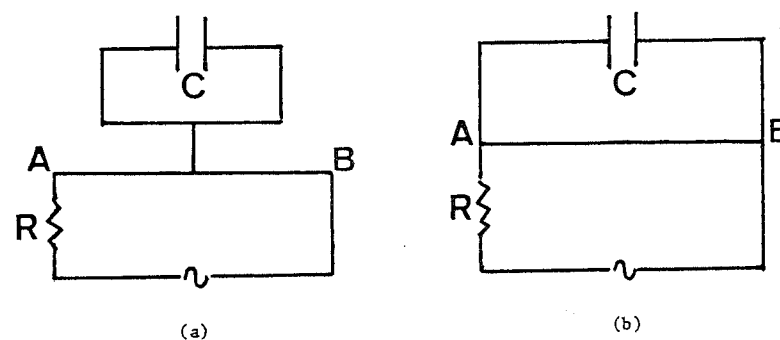


Figure 3 - The short circuited capacitor(A-C)



TABLE 4  
(Scientific students, second year of University)

| Circuit | % correct answers | % wrong answers | % no answer | Total |
|---------|-------------------|-----------------|-------------|-------|
| (3b)    | 17                | 75              | 8           | 100   |

Distribution of answers for circuit (3b).

TABLE 5  
N = 36

|                                                                           |      |
|---------------------------------------------------------------------------|------|
| Current partition                                                         | 22 % |
| Current in the capacitor is always zero (no matter what the frequency is) | 39 % |

Distribution of the answers for circuit (3b) (extract).

TABLE 6  
(Scientific students, end of second year of University)

| Circuit | % correct answers | % wrong answers | % no answer | Total |
|---------|-------------------|-----------------|-------------|-------|
| 4       | 77                | 13              | 10          | 100   |

frequencies, an increasing part of the current can "pass through" the branch including the capacitor.

48 students were tested at the end of the second year of a scientific university. Exercise (3a) was correctly treated by all these students. The results concerning (3b) are shown in tables 4 and 5.

Here the kind of reasoning which would have led to the correct answer for a direct current (the capacitor is short circuited) is no longer correct. But A-C seems to be always treated as D-C : the problem of frequency was never considered. The use of current reasoning only systematically continued.

#### IV - The fluid metaphor as an "intuition"

Numerous authors have emphasized "current reasoning". The "fluid metaphor" and the circuit considered as pipes can explain the results. We say that it is a very common "intuition" (in the sense given by Halbwachs [12]), shared by most students (and also adults, and even physicists...). Yet it would be deceitful to identify this intuition with a precise physical concept.

On the contrary, it appears that this fluid possesses qualities which, for a physicist, are conceptually different (though linked). It is at once a fluid of matter and a fluid of energy (corresponding, in this case, to the "energy view" described by Rhôneck [13]).

If this hypothesis on the primary representation of the students is correct, one can suppose that this "intuition" is "too rich", and leads to contradictions not easy to overcome, for example, when they consider current conservation in a serial circuit : how can a student explain that the (material) fluid conserves itself and, at the same time, the fluid (of energy) "exhausts" itself little by little ? Especially when this last phenomenon is so clearly visible (lighting of the bulb and wearing of the battery) !

#### V - Sequential reasoning and current direction

Recently authors emphasized the difficulties students have when considering the electric circuit : they used a sequential analysis of the circuit rather than a global one of the circuit as a system. This latter has a "before" and an "after" ; the "before" determines univocally the

"after", without any feedback [14,15].

In our opinion, the "moving fluid metaphor" is tightly linked to this kind of reasoning. Indeed, to follow a sequential reasoning, one needs to rely on a representation of "something" (a fluid) which moves from one point to another, followed sequentially all along its path. This fluid must also have a direction of movement (no matter if it is the conventional one, or the "displacement of electrons"). So it is tempting to propose a situation where this direction is not immediately given. It was the purpose of the exercise shown in Fig. 4.

"A and B are two identical condensers. They are charged by connecting the switch. When completely charged, the generator is taken away. The circuit is then connected again. Say which assertion is correct :

- A will be discharged before B
- A will be discharged after B
- A and B will be discharged at the same time."

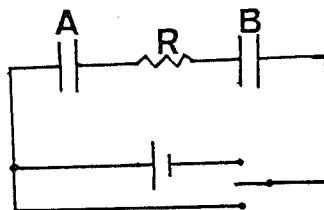


Figure 4 - Charge and discharge of two identical condensers.

Closset [14] asked a similar question but he looked for the charge of condensers, in presence of the generator. He found a large number of assertions that one condenser would be charged before the other (sequential reasoning). Our results, quoted in table 6, were quite different.

So it seems that, when the students cannot refer to an "obvious" movement direction for the fluid, their attention is drawn much more towards the symmetry of the situation. This situation is, of course, exceptional. Nevertheless, it may help us to show that, if the "moving fluid metaphor" is kept as the basic representation by students, it is also an "oriented" fluid.

## VI - Some conclusions

In our quest for the triangular relationships between cognitive representations, electric diagrams as graphical language, and electric diagrams as intermediaries for the physicist, we have been able to show the very great generality of the use of these diagrams in terms of current.

The other absolutely necessary concept for the analysis of an electric diagram, the electric potential, is missing. We interpret this by saying that there exists a primary representation, "an orientated moving fluid" (such a representation seems to be shown in other domains of physics [16]).

We believe also :

- a) that this representation, even rough, is of great efficiency, when supporting current reasoning, for a large class of problems commonly encountered by pre-university students (typically, problems like : "Does current pass ?"), and thus an additional reason for the strength of this representation.
- b) that this representation is not at all contradictory with other more elaborate reasonings ("constant current model", "sequential reasoning"...), but, on the contrary, allows them at the same time.
- c) that the didactic question which appears as one of the harder to solve is that of learning the notion of electric potential.

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## PROBLEM REPRESENTATIONS AND PROBLEM-SOLVING PROCEDURES IN ELECTRICITY

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### INTRODUCTION

Electricity is a domain of physics where diagrams play an important part because it is practically the only way to communicate the whole information existing in a circuit. Learning about electricity, even at a relatively elementary level as in a junior high school, supposes that students are able to understand the meaning of a circuit diagram, even of the simplest kind that includes only a battery and two resistors. Reading a circuit diagram and decoding it requires that a student masters the following perceptual skills:

- knowing the symbolism representing each component (wire, battery, resistor and any other component);
- not being embarrassed by a formal representation code as the one requiring that wires be drawn as perpendicular lines instead of smooth curved lines;
- analyzing the whole diagram to recognize if the drawing represents a real circuit, that is, for example, if the circuit is well closed (with no broken branch), or if some components are not short-circuited;
- then recognizing what components are in series and/or in parallel.

Although these perceptual skills are relatively primitive they are closely related to the understanding of basic concepts such as current and voltage. Such an understanding is a prerequisite to the successful solution of textbook problems in electricity. They help students build a useful problem representation. A problem representation is a cognitive structure corresponding to the given problem. It is constructed by a solver from his/her knowledge base. If the problem representation is built incorrectly, then the solving will be wrong. In mechanics, Chi et al. (1981) have shown that novices base their representation on the problem's literal features instead of abstract physics principles as experts do it.

In this paper, we will show how students describe and categorize circuits drawn with different shapes but electrically similar. By these first studies we will be able to infer some problem representations and then to see if the quantitative problem solving can be explained by these representations.

# 1 - STUDY ONE: CIRCUIT DESCRIPTION

The objective of the first study was to observe how subjects describe verbally electrical circuits presented in the form of diagrams. The subjects were ten undergraduates who were not attending an electricity lecture when this experiment was performed, but who had been taught in electricity at highschool.

24 diagrams were presented to each student on a card. Each diagram represented one of the four following basic circuits:

- a circuit S including two resistors in series;
- a circuit P including two resistors in parallel;
- a circuit PS including in parallel one resistor and a set of two resistors in series;
- a circuit SP including in series one resistor and a set of two resistors in parallel.

These basic circuits were pictured with different global shapes and different component dispositions. However their topologies were conserved. So there were 3 diagrams for the circuit S, 5 for the circuit P, 6 for the circuit PS and 10 for the circuit SP. The subjects were asked to describe these circuits.

The results are shown on Figure 1 where the number of correct descriptions is given for each diagram. If the criterion of at least 8 correct answers out of 10 is chosen as a successful description criterion, only 9 diagrams are well described. On the other hand, more than half of the subjects fail to describe correctly 9 circuit diagrams. And among these ones, 5 represent the circuit SP.

These results suggest that graphic representations of a same circuit are not equivalent for different novices. Some

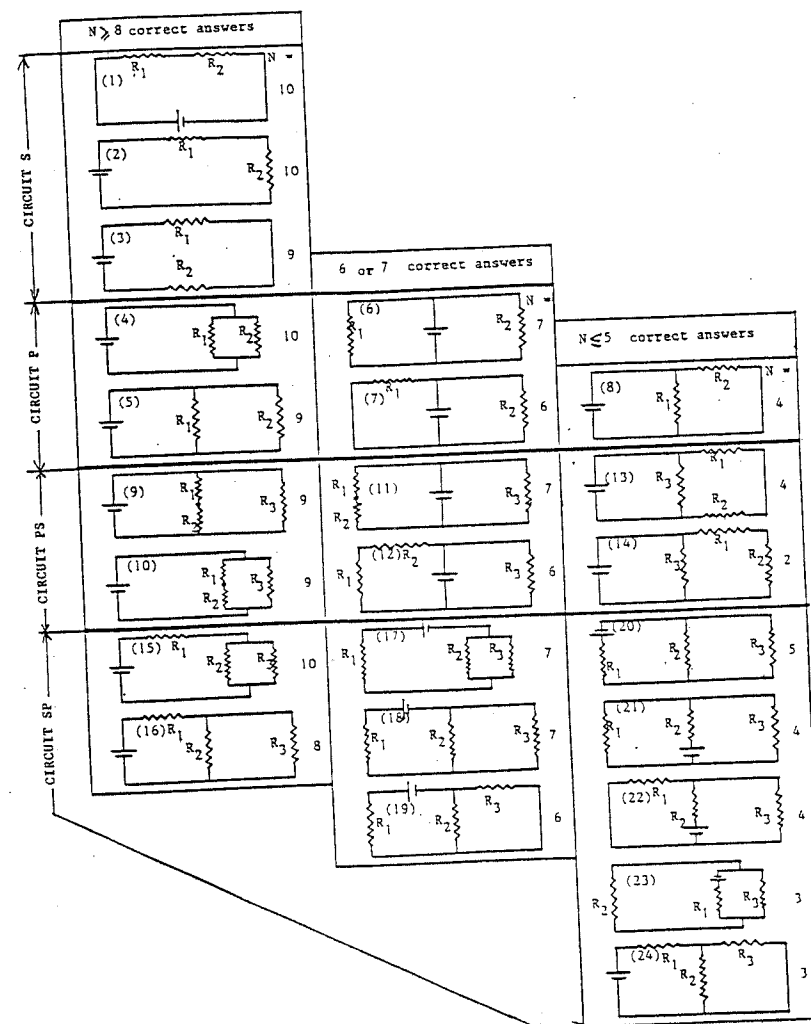


Fig. 1 - CIRCUIT DIAGRAMS PRESENTED TO THE STUDENTS. The number of correct descriptions is given beside each diagram.

of them are better analyzed than others.

If we set aside the three diagrams picturing the circuit S, which are described correctly, we note that the students perform with a high rate of success on the description task when two resistors in series are drawn aligned as on the Diagrams 8, 9 and 10, or when resistors in parallel are drawn geometrically parallel as on diagrams 4, 5, 9, 10, 15 and 16. But an examination of the students' wrong answers reveals some striking features on how novices in fact analyze some circuits.

For example, when two resistors in series are not lined up, this type of interconnection is then poorly recognized (Diagrams 13 and 14). On the other hand, in Diagram 24, the resistors  $R_1$  and  $R_3$  are seen in series although they are not connected this way, but they are aligned. Whenever two resistors in parallel are not drawn on parallel lines, the students are confused (Diagrams 8 and 24). It is even more curious that for Diagram 18 the students say both resistors  $R_1$  and  $R_2$  are in parallel and that for Diagrams 18, 20, 21, 22 and 23 all resistors displayed geometrically parallel are said to be in parallel, even if a battery is included in a branch as in Diagrams 21, 22 and 23.

All this suggests that novices in electricity base their description of circuits presented in a diagrammatic form on surface features rather than on physics principles, as Chi et al. (1981) have already shown for mechanics problems. Here we mean by surface features, similarities in graphics which induce students to say that

- all lined up resistors are in series (even if a node exists between them);
- all geometrically parallel resistors are in parallel (even if a battery is included in one of the parallel branches).

These representations are constructed independently of the deeper structure based on the physics principles which state that

- for all components in series, the same current passes through each component;

- for all components in parallel, an identical potential difference is applied to each component.

## 2 - STUDY TWO: CIRCUIT SORTING

The second task was given to all students who had previously done the first one. The instruction was to sort the 24 diagrams into groups of similar circuits. When they had finished this, they were asked to explain the reasons for their groupings. The global results are shown in Figure 2.

All students categorized well the 3 diagrams of the circuit S, whatever the resistor configuration was. But only 3 students out of 10 succeeded in the whole sorting task: they found that all the diagrams represented only 4 circuits, in spite of their different pictures. The other students found a variable number of groupings: from two to eleven!

When students perform well on the sorting task, they do it expertly, looking at the component configuration and the nodes, as a student explained it explicitly: "(In spite of different wire configurations) thus we find the very same diagrams owing to the connection points".

On the other hand, when a student fails there can be two reasons:

- either the student is completely unable to find a useful criterion enabling to sort the diagrams, as Subject 1 who put all circuits, but the three S, in one group because "they have branches in parallel";

- or he/she uses as criteria the surface features, that is the geometrical characteristics of the diagrams:

- external shape,
- generator position,
- existence of a small loop,
- resistor configuration (in straight line or geometrically parallel).

In Figure 3, we present two examples of groupings made by two students who obviously sorted the diagrams on the basis of the geometrical features. The reasons they gave were of course wrong from the physicist's point of view. Subject 10 said "I placed these 5 cards together because of the shape of

Fig. 2 - CIRCUIT SORTINGS MADE BY STUDENTS.

| CIRCUITS |    |   |    |   |   |    |   |   |    |  |   |   |   |   |
|----------|----|---|----|---|---|----|---|---|----|--|---|---|---|---|
| S°       | N° | S | P  |   |   | PS |   |   | SP |  |   |   |   |   |
| 1        | 2  |   | 21 |   |   |    |   |   |    |  |   |   |   |   |
| 2        | 4  |   |    |   |   |    |   |   |    |  |   |   |   |   |
| 3*       | 4  |   |    |   |   |    |   |   |    |  |   |   |   |   |
| 4        | 4  |   |    |   |   |    |   |   |    |  |   |   |   |   |
| 5        | 11 |   | 2  | 2 | 1 | 3  | 2 | 1 | 6  |  |   | 2 | 1 | 1 |
| 6        | 4  |   |    |   |   | 13 |   |   |    |  |   |   | 3 |   |
| 7        | 8  |   | 2  | 2 | 1 | 1  | 9 |   |    |  | 4 |   | 2 |   |
| 8        | 10 |   | 4  |   | 1 | 2  | 3 |   | 3  |  | 2 | 2 | 2 | 2 |
| 9        | 5  |   |    |   |   |    |   |   | 5  |  |   | 5 |   |   |
| 10       | 3  |   | 5  |   |   | 16 |   |   |    |  |   |   |   |   |

(\*) 1 error between PS and SP

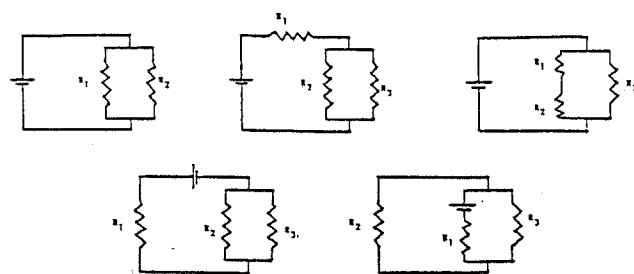
The number in each box represents the number of diagrams grouped together by Student "S\*". Column "N\*" is the total number of groupings. The empty boxes mean that the sorting is correct.

the resistances in the circuit, in the five figures I can see them being parallel" (Fig. 3a). In fact his implicit criterion was the presence of a small loop, and this independently of the resistor configuration. Subject 7 justified one of his groupings (Fig. 3b) in saying: "there are two independent circuits, each circuit having 2 resistors in series". The place of the generator induced this student to share mentally the circuit into two independent parts, each including the generator. Other sortings based on the geometrical characteristics support the idea that the novices in electricity categorize diagrams from surface features.

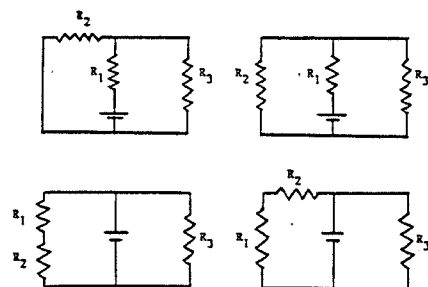
But some students behave differently. Consider Subject 5 who made the greatest number of groupings. When we examine the justifications for his sortings, all are right. He was able to describe diagrams correctly, so he had quite a good understanding of what a circuit is. However his level of expertise was not high enough, so that he was disturbed by the surface features of the diagrams. Figure 4 presents how he sorted the 5 circuits P. Each of his groupings is based on the circuit geometry: the generator place for the two first categories and a small loop for the third.

Thus between the most naive students in electricity who sort diagrams on the basis of the surface features and the experts (or the more advanced students) who do it on the basis of the physics principles, there are students who mix both strategies. Their representation of the circuits are characterized by the underlying electricity principles but these principles are constrained by the surface features of the pictures.

To summarize the second study, we were able to replicate the initial finding that novices in electricity categorize circuit diagrams by the surface structure of the diagram, that is in this case by its geometry rather than by its topology. Furthermore, advanced novices begin to sort diagrams by electricity principles, although their groupings are still constrained by geometrical considerations.



3a - Circuit grouping made by Subject 10

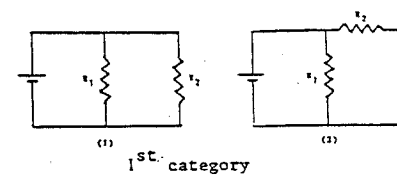
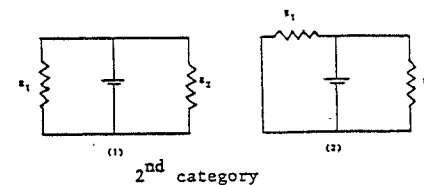
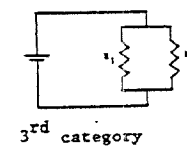


3b - Circuit grouping made by Subject 7

Fig. 3 - CIRCUIT SORTINGS BASED ON CRITERIA OF SURFACE FEATURES

3a - Presence of a small loop.

3b - Position of the battery placed right in the middle.

1<sup>st</sup> category2<sup>nd</sup> category3<sup>rd</sup> categoryFig. 4 - CIRCUIT SORTINGS MADE ON CRITERIA OF PHYSICS PRINCIPLES  
CONSTRAINED BY SURFACE FEATURES.

### 3 - STUDY THREE: NUMERICAL PROBLEM SOLVING

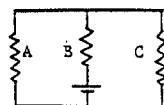
As novices are inclined to build problem representations in electricity from geometrical features rather than from physics principles, when they are asked to solve problems with numerical values it is likely to find these naive representations in their solutions. The aim of this study was to see if our hypothesis was justified.

One student (Subject 10) who had performed the two previous experiments was asked to solve 15 different exercises, each one being based on a circuit chosen among the 24 already described. Numerical values were attributed to each resistance and to the emf of the battery. There were three kinds of statements:

- Statement A (for 11 circuits: 1 S, 4 P, 3 PS and 3 SP),  
"What is the current passing through the point A?"
- Statement B (for 2 circuits SP),  
"We want to replace the circuit shown above by another circuit including the same battery in series with a single resistor R. Find the value of R."
- Statement C (for 2 circuits SP),  
"Is it possible to replace resistors X and Y by a unique resistor R with no change of the current in resistor Z? If yes, find the value of R."

The protocol analysis enabled us to observe how the student grouped the resistors in order to calculate the requested entities. There was a real good agreement with the resistor associations made for the description and the sorting tasks. So the subject did not modify his circuit representations for 11 problems out of 15 with regards to his initial descriptions.

We give below an example of the way he solved a statement B-problem on a circuit represented by the following diagram.



To calculate the requested resistance R, he made two successive steps: first of all, he grouped together resistors A and B in parallel and calculated the corresponding equivalent resistance; then he associated it in parallel with resistor C. In fact, basically the student regarded resis-

tors A, B and C as associated in parallel, which was exactly what he was thinking because in the initial description task, he had said: "They (all the resistors) are in parallel."

Through this example, we highlight how the representations based on the geometrical properties of circuit diagrams influence the solving processes of textbook problems. This result should be compared with the result of an experiment reported by Caillot (1983). In this experiment, 10 American undergraduates were asked to find an equivalent resistance between two terminals when the values of all resistances were given. The number of resistors increased from one circuit to another. As the circuit became more complex, more and more students used purely geometrical characteristics to associate resistors in order to get an equivalent resistance. For example, some students thought that the concept of equivalent resistance could be applied to resistors drawn lined-up, but separated by a junction. So they were able to define an equivalent resistance by summing the values of resistances as if these resistors were in series.

### 4 - DISCUSSION

The aim of this research has been to understand why some students fail to solve correctly DC-circuit problems. Some explanations could be probably found in the students' misconceptions of the electricity concepts such as current and potential difference, or even in a sequential reasoning. However these are not sufficient because they do not take into account an important characteristic of the DC-circuit problems: the presence of a diagram included in the statement. Our hypothesis was that reading and decoding correctly the information displayed on the diagram contribute to an efficient problem representation. So a poor circuit analysis will certainly lead to a wrong solution. Our results confirm entirely this point of view, but they give us more information on criteria used by students to analyze a circuit.

In mechanics, Chi et al. (1981) have identified in the problem statements what relevant features are used by novices



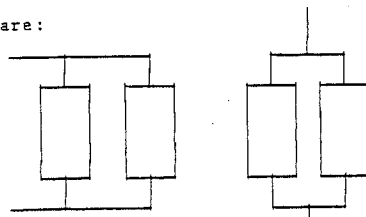
to plan their solving. These features are literal objects and terms such as "pulley", "friction", etc. Here we have shown that the relevant features which trigger the novices' solving are specific geometrical resistor configurations -alignment and parallelism- and this, independently of the presence of a junction or a battery on the branch under consideration. These two geometrical configurations are very similar to the canonical diagrams largely diffused in class when the resistor groupings are taught: lined-up resistors for resistors in series and parallel resistors for the ones in parallel.

Thus, in the student's mind, a specific concept (e.g. connection in series) becomes so closely associated with an image (aligned resistors) that there is no difference left between the concept and its pictorial representation. At this point, we can say that the canonical circuit drawings play the role of prototypes of "in-series" and "in-parallel" concepts (Caillot & Cauzinille-Marmèche, 1984). In cognitive psychology, prototypes approximate a person's image of an object class. They represent an average of the appearances of those class members which are regarded as typical instances (Seymour, 1979).

The prototypical circuits are:



"In-series" prototype



"In-parallel" prototypes

A circuit picture more or less similar to a prototype will affect the novice's answers to the description and categorization tasks. So a circuit of two lined-up resistors with a junction between them from which a branch starts, is pictorially closer to the "in-series" prototype than two resistors actually in series but drawn perpendicular. Therefore it will be recognized and named as an "in-series" circuit.

In this study, we have shown that a novice builds mental representations of DC-circuit problems from surface features which in this case are of pictorial nature. Thus probably the novice stores in his/her memory, concepts such as "to be connected in series" or "in parallel" under a prototypical image, instead of a list of their attributes based on physics principles underlying the properties of such circuits.

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# PUPILS' REASONING WITH REGARD TO AN ELECTROMAGNET

Björn Andersson

## INTRODUCTION - A DISCOVERY AND A QUESTION

In connection with the development of Elementary School Science during the sixties and seventies, stress was laid on the importance of providing the pupils with experience of scientific processes such as classification, control of variables and reasoning with models. This inspired the author to invent a simple laboratory investigation about electromagnetism a few years ago. First, as a demonstration, a plastic-insulated wire was wound round a soft-iron bolt and connected to a voltage source. This system was then placed close to a pile of paper clips and the switch was turned on. Some of the paper clips fastened onto the bolt. When the switch was turned off, they fell away. The pupils were then asked to consider what variables affected the strength of the electromagnet. The most common suggestions were the intensity of the current, the number of coils and the material the bolt was made of. After that the pupils were allowed to investigate several of these variables on their own. They were supplied with plastic-insulated wires, bolts of various materials, paper clips and voltage sources. The lesson went well. Both pupils aged 14-15 years and prospective elementary school teachers worked with interest and in a constructive manner.

On one occasion a year or two ago there was a shortage of plastic-insulated wire. An old spool of enamelled copper wire was available, however. The introductory demonstration was done with this wire. The enamel had been scraped away from the end of the wire in advance. When the laboratory material was then dealt out to the pupils, some groups received enamelled wire, others plastic-covered. Before the teacher had a chance to point out that the enamel had to be scraped away from the end of the wire, one group that had been given plastic-covered wire protested. They said it was impossible to make an electromagnet with that wire. They

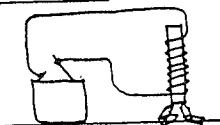
wanted the other one instead.

In the conversation that followed it became evident that the pupils thought that the enamelled wire, which is manifestly copper-coloured, was completely uninsulated and that the current therefore flowed into the bolt and made it magnetic. Plastic obstructed the current, so that the plastic-covered wire was considered useless. This "theory" came as a surprise to the author, who had never thought of the variable insulated - uninsulated at all before, probably because it did not fit in with his own model of an electro-magnet.

Was the pupils' theory a coincidence, or one that was commonly held? To answer this question, the following two test problems were eventually constructed.

## TWO TEST PROBLEMS

### Problem 1



A pupil is experimenting with electro-magnets. He winds electric wire round rods of different materials and connects the ends of the wire to a battery (see figure). Sometimes the pupil succeeds and then the electro-magnet attracts some paper clips.

In the plastic bag you have been given there are two systems:

System A: Iron bolt, wound round with uninsulated electric wire.

System B: Iron bolt, wound round with plastic-insulated electric wire, (the plastic is scraped off from both ends of the wire).

What will you see when system A and system B are each connected to a battery? Put a cross in one of the boxes below.

- ☐ Both A and B attract paper clips.
- ☐ A, but not B, attracts paper clips.
- ☐ B, but not A, attracts paper clips.
- ☐ Neither A nor B attract paper clips.

How did you think out your answer?

### Problem 2

A figure shows six experiments (A,B,C,D,E,F). The same kind of wire is used in all the experiments and current always flows through it. But the wire is wound round different types of material. (This text is followed by six figures similar to that in Problem 1. An arrow points to the core of each spool and indicates what it is made of.)

A: wood B: iron C: plastic D: silver E: copper F: stearin

Do you think the paper clips are picked up in any of these experiments? Put a cross by the experiment or the experiments in which you think the paper clips are picked up. Explain how you thought this out.

Comments: Problem 2 was constructed so that it could be correlated with Problem 1. The pupils who believe that current enters the core of the spool in Problem 1 perhaps believe that the systems containing metal in Problem 2 (B,D and E) function as electromagnets.

### THE GROUPS INVESTIGATED

These two problems were given to 94 pupils in Form 8 (aged about 14 years) in May 1984. All these pupils had had lessons on magnetism and electromagnetism during the school year. The concept of magnetic field was included and it was established that electric currents give rise to magnetic fields. In addition to the above, 23 pupils in Form 9 were tested in the same way.

Interviews of an exploratory nature were also carried out, using the pupils' written answers as a starting-point. (18 pupils)

### RESULTS

#### Problem 1

The following answer categories are found:

- I NO RESPONSE
- II SYSTEM A ATTRACTS PAPER CLIPS, B DOESN'T

- A. No reason given.
- B. If plastic insulation, no effect.
- Because B is insulated. Doesn't attract paper clips so easily.
  - B has plastic-covered electric wire and then nothing happens, of course.
  - A isn't insulated, so it can pick up the paper clips.
  - If the wire is insulated, then it doesn't come into contact with the piece of iron.
- C. Plastic stops current, magnetism, etc from entering the the bolt.
- C<sub>1</sub> Current
- The plastic that is round the wire in B insulates the current from reaching the piece of iron. Current has to reach this for it to be able to pick up the paper clips.
  - As B is insulated, there is no contact with the piece of iron. The current then goes through the electric wire only. The piece of iron doesn't get charged.
- C<sub>2</sub> Magnetism etc
- When there's plastic round it doesn't give off any magnetism.
  - B doesn't attract any paper clips because it's plastic-covered electric wire on the piece of iron, because then the radiation from the piece of iron is stopped.
- D. Other
- B has plastic round it, of course, and that maybe pushes the paper clips away.
- III BOTH SYSTEMS A AND B ATTRACT PAPER CLIPS
- A. No reason given.
- B. Same wire in both/plastic doesn't matter.
- It's the same material under the plastic.
  - It doesn't matter what there is round it, it's the electric wire that matters.
- C. Current passes along both wires.
- Current passes through them and, even if B has plastic-insulated wire, it's peeled off at the ends, isn't it, so the current goes through them, too.
- D. Magnetism/magnetic field goes through the plastic.
- The magnetic field gets so strong that it goes through the plastic. In A there wasn't any plastic, so it also becomes magnetic.

E. Other.

IV SYSTEM B ATTRACTS PAPER CLIPS, A DOESN'T

- A. No reason given.
- B. Insulation necessary to obtain a magnetic field.
- To form a magnetic field inside the wire, the wire must be insulated, otherwise the wires lie on top and interfere with each other.
  - When it's wound round with insulated wire, a magnetic field is formed. With uninsulated wire the piece of iron also gets charged and there's no magnetic field.
- C. Other.

#### Problem 2

The following categories are found:

- I NO RESPONSE
- II ONE OR MORE METALS ARE CHOSEN  
(B-iron, D-silver, E-copper)
- A. No reason given.
- B. They are metals.
- They are metal rods. (B,D,E)
  - Iron, silver and copper are metals, of course. The other materials aren't. (B,D,E)
- C. The substances conduct electricity/They become magnetic when current passes through them
- All metals conduct electricity, some more, some less. (B,D,E)
  - Wood, plastic and stearin do not conduct electricity. They cannot pick up paper clips. (B,D,E)
  - The ones I've put a cross by are metals. They attract the paper clips because when you send current through metals, they become magnetic. (B,D,E)
- D. The substance is magnetic/the substances are magnetic.
- The piece of iron is magnetic. (B)
  - Iron and copper are magnetic. (B,E)
  - Wood, plastic and stearin don't fasten onto a magnet, but silver, copper and iron do, I think. (B,D,E)
- E. Other

## III ALL OTHER CHOICES

A. No reason given.B. Other.

- A magnetic fields is formed round all the spools with current. (A,B,C,D,E,F)

Table 1. PROBLEM 1: Distribution of categories (%)

|               | I. No response | II. A attracts B doesn't |    |                |                |   | III. Both A and B attract |    |   |   |   | IV. B Attracts A doesn't |   |   |
|---------------|----------------|--------------------------|----|----------------|----------------|---|---------------------------|----|---|---|---|--------------------------|---|---|
|               |                | A                        | B  | C <sub>1</sub> | C <sub>2</sub> | D | A                         | B  | C | D | E | A                        | B | C |
| Form 8 (n=94) | 0              | 11                       | 32 | 18             | 4              | 3 | 10                        | 12 | 3 | 2 | 3 | 0                        | 0 | 2 |

II. A. No reason given

B. If plastic, no effect

C<sub>1</sub> Plastic stops currentC<sub>2</sub> Plastic stops magnetism

D. Other

III. A. No reason given

B. Same wire in both/plastic doesn't matter

C. Current in both wires

D. Magnetic field goes thorough plastic

E. Other

IV. A. No reason given

B. Insulation necessary for magnetic field

C. Other

Table 2. PROBLEM 2: Distribution of categories (%)

|               | I. No response | II. One or more metals chosen |   |    |    |   | III. All other choices |   |
|---------------|----------------|-------------------------------|---|----|----|---|------------------------|---|
|               |                | A                             | B | C  | D  | E | A                      | B |
| Form 8 (n=94) | 3              | 17                            | 9 | 40 | 20 | 9 | 0                      | 2 |

II. A. No reason given

B. They are metals

C. The substances conduct electricity/become magnetic when current passes through them

D. The substance/substances are magnetic

E. Other

III. A. No reason given

B. Other

## ANALYSIS

In the introduction, it was reported that some pupils had said in a lesson that an electromagnet works because a current from an electric wire flows into a bolt and makes it attract paper clips. This prompted the question: "Is this theory common?" The pupils' responses to test problems 1 and 2 provide evidence for an answer in the affirmative. With regard to Problem 1, 18% of the pupils declare explicitly that plastic hinders the current from going out into the bolt, and that this is why system B does not work (II C<sub>1</sub>). Furthermore, 32% of the pupils believe that if there is plastic round the wire, there will be no effect, that is, the system does not pick up the paper clips (II B). This is probably the same idea as in II C<sub>1</sub>, but expressed more vaguely. The interviews provide a certain amount of support for this interpretation. Of the 18 pupils interviewed, two belong to category II B according to their written answers. In the interview, when they are to explain more precisely how they thought it out, one immediately says that current passes from the uninsulated wire into the bolt. The other one throws out the same idea after a moment's conversation, but wavers between saying that the plastic hinders magnetism and it hinders current from entering the bolt.

Another point that can be made about Problem 1 is that, out of 8 pupils placed in category III B or III C after the written test, five go over to category II C<sub>1</sub> during the interview. When the interviewer asks them to explain in more detail how they reasoned when they wrote their answers, especially with respect to how the bolt becomes magnetic, they then begin to inspect systems A and B more carefully, attempting to articulate a theory at the same time. It seems

to be this process that causes them to change their minds.

As far as Problem 2 is concerned, we may observe that 40% of the pupils, in explanation of their choice of systems capable of attracting paper clips, claim that the substances conduct electricity, or that they become magnetic when current enters them (II C). Out of the pupils in this category, 73% choose all the metals. The remainder choose, with few exceptions, iron and copper - the interviews show that they are uncertain whether silver conducts electricity. The answers in category C indicate, in other words, that the pupils believe that once current has gone out into the metal, an effect is obtained, that is, the system attracts paper clips. The answers in category II B probably express the same idea, but less clearly. The pupils in category II D in the answers to Problem 2 say that the system can attract paper clips on condition that the substance is magnetic. Of these pupils, 65% are of the opinion that iron is the only magnetic substance in the problem, while 23% believe that all the substances are magnetic. One may guess that most of the pupils in II D argue as follows: The substances have to be magnetic to be able to attract paper clips. Only iron, out of all the substances in Problem 2, is magnetic. So I'll put a cross by B ... Perhaps some pupils think that the current certainly goes out into all the metal bolts but only exerts an effect if the substance is "magnetic".

To sum up, we may conclude that the answers, both the written ones and those in the interview, indicate that at least half of the pupils possess the idea that current enters the bolt and causes it to become magnetic. For this reason, uninsulated wire has to be used for winding round the bolt. This estimate is probably on the low side.

#### AN ATTEMPT AT INTERPRETATION

The concept of experiential gestalt was introduced by Lakoff and Johnsson (1980). A given gestalt is made up of a number of different components, which together form a whole that is more fundamental than the parts.

Children begin to construct the experiential gestalt "causality" at a very early age. The small baby pulls at its cover, hits a rattle, throws away its bottle. A common factor in these and many other actions is that we have an agent, who, either directly with his/her own body or by means of an instrument, affects an object (Lakoff and Johnsson use the English word patient instead). The agent is the energy source and the object is the energy receiver. There is only one agent and one object.

According to Lakoff and Johnsson (p 71) these components characterize

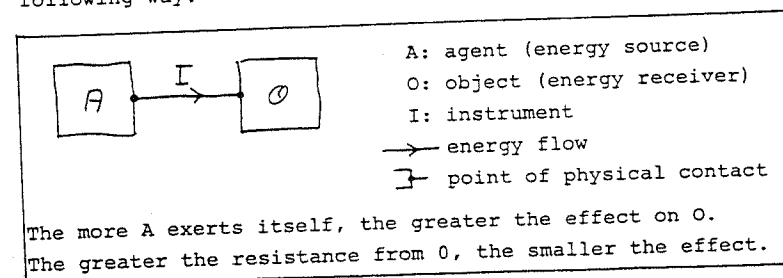
"a prototype of causation in the following sense. They recur together over and over in action after action as we go through our daily lives. We experience them as a gestalt; that is, the complex of properties occurring together is more basic to our experience than their separate occurrence."

Bit by bit, as the child explores the world around it, the experiential gestalt is extended. The child discovers, for example, that the more it exerts itself, the greater the effect on the object, and also that different objects offer different degrees of resistance.

There is no need for the instrument to be a rigid body in continuous contact with agent and object. The child (A) throws a snowball (I) to knock off his friend's cap (O). Mother (A) directs the jet of water (I) onto the flowerbeds (O).

The agent need not be a person. A wave (A) rolls in towards the shore and demolishes the sandcastle (O).

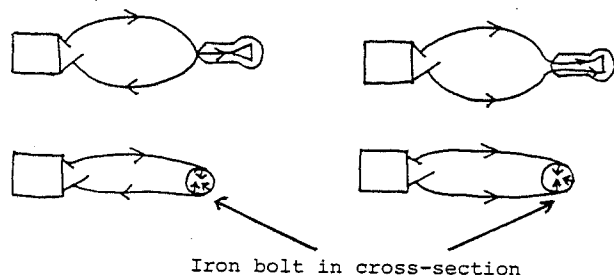
We may sum up the experiential gestalt causality in the following way:



This simple gestalt is a powerful organizer of everyday experience. We use it daily and at every moment to guide our actions and to understand what is happening around us. Our language is full of words of which the meanings provide examples of the "gestalt" in question: hit, hammer, plane, paint, dig, sculpture, hug, caress ...

The pupils' theory of how an electromagnet works may be seen as an application of the experiential gestalt causality. The battery is an agent, which exerts an effect on the bolt - the object, with the current as its instrument. To obtain an effect, there has to be contact between the instrument and the object. The plastic hinders this contact. Alternatively, the current may be regarded as an agent, which produces an effect when in contact with the bolt.

There is a striking similarity between the answers we obtained about the electromagnet and the, by now well-known, answers from school pupils regarding how you connect a bulb to a battery to make the bulb light. See the figures below!



#### FINAL REMARKS

The experiential gestalt causality is simple and concrete - one agent, one instrument, one object, contact. Scientific explanations of such systems as electromagnets and circuits with lamps and batteries are abstract and complex. They demand that many different concepts should be linked together in the process of understanding. The problem the teacher faces is two-fold. For one thing, pupils prefer to organize the world around them with the aid of the ex-

periential gestalt causality in the simple and concrete form described above. For the other, the explanations of physics, which in themselves encompass elements in the experiential gestalt causality, are abstract and complex. It is reasonable to suppose that the teacher is in a better position if he/she is aware of the way pupils reason. In that case, one can challenge their conceptions with, for example, experiments which give results that are contrary to the pupils' predictions. (Compare this with the answers to Problem 1, which show that whole classes may make such predictions.) This may increase the pupils' inclination to try to understand the alternative explanations of physics, but this is only the first step along the way all the same. The pupils' chief difficulty is to understand the scientific models, which are hypothetico-deductive in nature and include concepts referring to something "out there", which we cannot see but have to imagine. Examples of such concepts are the atom, light ray and magnetic field. How to stimulate the pupils to construct, link together and use concepts of this kind presents a great challenge to us all.

Reference: Lakoff, G and Johnson, M. Metaphors we live by.  
The University of Chicago Press, 1980

# *STRUCTURAL UNDERSTANDING AND PROBLEM-SOLVING SKILL<sup>1</sup>*

Mary S. Riley

## *1.0 Introduction*

A common instructional objective in domains of science and mathematics is the ability to use formulas and arithmetic procedures to solve problems. Although students are explicitly taught the relevant formulas and principles, are shown worked-out examples, and are given practice, they frequently experience considerable difficulty when asked to solve similar problems. The reason proposed here is that the difficulties are due to a lack of understanding of important structural relations between the elements in a problem domain. Further, it is proposed that performance can be improved by instruction that takes these relations explicitly into account.

The analyses also show that even when correct solutions occur they can result from mechanical application of rules and formulas with little understanding of structural relations. When this happens students are left with a weak basis for correct performance, for retaining what they learn, and for learning related subject material. Therefore, understanding of the structural relations needs to be tested explicitly. To do this, the standard notion of instructional objectives needs to be expanded to include the knowledge structures that produce the behavior as well as the behavior itself (Greeno, 1976).

An important goal of this research is to identify general concepts that could lead to important gains in structural understanding at the outset of learning a new domain. Recent comparisons of the knowledge underlying expert and novice performance in various domains suggests that problem-solving skill depends in large part upon having an understanding of important structural relations between the entities in a domain. This sophisticated understanding, built up over thousands of hours of experience, enables experts to construct elaborated problem representations that guide efficient solutions. Novices lack this understanding, of course. They rely on local problem features and weak general strategies that often lead to inefficient or unsuccessful solutions, especially as problem complexity increases. Novices nevertheless understand general concepts that might be used to structure problem situations in ways that could result in improved performance and provide a basis for learning more advanced (domain-specific) concepts.

1. The research reported herein was supported by a joint contract with the Navy Personnel Research and Development Center (NPRDC) in San Diego, California, and the Office of Naval Research (ONR). The opinions expressed do not necessarily reflect the position or policy of NPRDC or ONR, and no official endorsement should be inferred.



Structural understanding in problem solving has been discussed before by Gestalt psychologists. Wertheimer's analysis (1945/1959) of learning and instruction in mathematics distinguished between meaningful solutions based on an understanding of the mathematical structure of a problem and solutions based on a rote application of algebraic formulas. This is not to say that a meaningful solution cannot involve formulas, rather what matters is whether the problem representation guiding the solution reflects an understanding of the structural requirements of the situation. Katona (1940) contrasted instruction that emphasized problem structure with instruction focused on memorization of problem-solving steps. These and other Gestalt analysis provided many compelling demonstrations of how structural understanding provides the basis for efficient and correct performance, retention of problem solutions, and transfer of new learning to novel problems having similar structures.

Structural understanding has also been discussed by educational psychologists concerned with meaningful learning. Brownell (1928) advocated teaching students an understanding of the mathematical structures underlying computational procedures and expressed concern that drill and practice encourages children to view mathematics as a set of unrelated facts and procedures. Bruner (1960), a psychologist associated with the mathematics curriculum reform movement in the late 1950s and early 1960s, made specific proposals for instructing mathematical structures in a way that takes into account student's cognitive capabilities. Based on his theory of intellectual development similar to Piaget's, he proposed that mathematical structures should first be presented in the form of concrete materials and only later in the form of abstract symbols. The idea was that the structural understanding children gained from interacting with concrete materials could then be applied to understand the structure underlying procedures involving more abstract symbols. Dienes (1966), who collaborated with Bruner, designed carefully planned sequence of exercises with concrete materials to highlight aspects of mathematical structures. However, instruction emphasizing structural understanding met with mixed results and therefore frequently abandoned in favor of more traditional drill and practice.

If structural understanding has been recognized for so long as important for student's performance, retention, and ability to transfer why is it usually neglected in instruction? The main reason is that both Gestalt psychologists and educational psychologists lacked the theoretical and methodological tools for providing explicit analyses of what constitutes structural understanding in a domain and how these structures relate to facts, rules and strategies during problem solving. In the absence of these analyses, it is impossible to define structural understanding as an explicit instructional objective and likewise impossible to determine how to test when a student has attained that objective. The lack of explicit analyses also makes it impossible to assess the implications of understanding specific structures for a student's ability to solve problems or learn more advanced topics. Furthermore, the

development and evaluation of methods for instructing structural relations requires an analysis of the understanding students have before instruction, and ways of assessing changes in understanding during instruction. The research reported here shows how recent work in problem solving and language understanding makes these analyses possible and discusses the implications for instruction.

The next section presents a theoretical analysis of structural understanding in basic electricity. The analysis is in the form of two computer simulation models that solve a target set of problems about direct-current (D-C) circuits. Differences between the models are proposed as an explicit characterization of the distinction between performing with and without structural understanding in this domain. Furthermore, the analysis shows how meaningful learning can result from the application of general concepts in the form of whole-parts relations between quantities.

## 2.0 Theoretical Analysis

Two computer simulation models were developed to represent hypotheses about the knowledge underlying problem-solving performance in basic electricity. Both models solve a target set of problems correctly, but differences in their problem representations reflect differences in their understanding of the structural relations between circuit quantities. The more adequate Model(2) includes knowledge of the quantitative structure of D-C circuits that is integrated with general knowledge of quantitative constraints. The less adequate Model(1) consists of a set of disconnected rules for solving specific problems. The analysis proposes that the knowledge included in Model(2) provides a better basis for skilled performance and continued learning and shows that additional problem-solving tasks are required to test whether this deeper understanding has been acquired.

The models were implemented as production systems containing two forms of knowledge for solving circuit problems: (1) a data base and (2) a set of production rules that operate on that data base. In the models, the data base contains mainly information about the current problem situation and knowledge of Ohm's and Kirchhoff's Laws expressed as formulas. It consists of a network of elements and relations between those elements, similar to the semantic networks developed in recent theoretical analyses of language understanding (e.g., Anderson, 1976; Norman & Rumelhart, 1975; Schank & Abelson, 1977). In these theories, schematic representations are used to organize the information in a sentence or story and to expand the representation of the message to include components that were not explicitly mentioned. Similarly, the process of solving a problem can be viewed as fitting the components of the problem into a coherent structure. Furthermore, as shown below, criteria similar to those used to judge whether or not one has understood a sentence or story can be applied to judge whether or not one has solved a problem with "understanding" (Greeno,

1976): (1) *coherence* —are the components of a representation related in an integrated structure?; (2) *correspondence* —does the representation include important structural properties of the problem?; (3) *connectedness* —to what extent is the representation tied to other components of a person's knowledge.

The models' production rules are of four general kinds: (1) Rules for parsing circuit schematics into declarative representations of the series and parallel relations between resistors; (2) Problem-solving strategies in the form of rules for coordinating this representation with the models' knowledge of circuit formulas, (3) Procedures for making inferences about circuit relations, and (4) Knowledge of additive and multiplicative whole-parts relations. The latter is represented as a Whole-Parts schema that includes: (a) procedures for instantiating quantities as whole and parts and (b) procedures for operating on wholes and parts to infer additional quantities or to infer the effects of changes in the values of circuit quantities.

The knowledge of circuit formulas, parsing procedures, and strategic knowledge included in Model(1) and Model(2) are identical. Both models also have procedures for making inferences about quantities constrained by additive and multiplicative whole-parts relations. The main difference between the models is in their ability to represent circuit quantities in terms of these relations. These differences are located in the models' Whole-Parts schema.

The general structure of the models' Whole-Parts schema is shown in Table 1. Consistent with recent proposals in problem solving and artificial intelligence (e.g., Bobrow & Winograd, 1977; Greeno, 1983a), the schema consists of three main parts: slots, schematizing productions, and procedural attachments. The slots indicate the kinds of objects the schema is designed to interpret — in this case, the objects are a Whole and two or more Parts. The schematizing productions interpret specific situations in terms of the objects in the schema. Model(2) has schematizing productions for interpreting circuit quantities directly in terms of Wholes and Parts; Model(1)'s schematizing productions are restricted to instantiating Whole-Parts relations between quantities in equations. Procedural attachments describe actions that can be performed on the objects in the schema, and correspond to the models' procedures for inferring additional values from known values. As shown in Table 1, each action is stored along with information about its prerequisites and consequences.<sup>2</sup> A procedural attachment is

2. The action of the first procedural attachment FIND-WHOLE is to combine the Parts, the prerequisite is that the value of all the Parts are known, the consequence is that the value of the whole is known. The action of the second procedural attachment is to separate the known Parts from the Whole; the prerequisites are that the values of all but one of the Parts (Part<sub>n</sub>) is known, and the consequence is that the value of Part<sub>n</sub> is known. (For additive Whole-Parts relations "separate" and "join" correspond to subtraction and addition, respectively; for multiplicative Whole-Parts relations, "separate" corresponds to division, "join" to multiplication.) Both models also have procedural attach-

Table 1

## General Structure of the Whole-Parts Schema

Slots: WHOLE, PART1, PART2, ...PARTn

## Schematizing Productions

Model(2): Productions for instantiating Whole-Parts relations between circuit quantities in the model's problem representation.

Model(1): Productions for instantiating Whole-Parts relations between quantities in equations.

## Procedural Attachments

Productions for making inferences about Wholes and Parts, e.g.,

## FIND-WHOLE

|               |                                       |
|---------------|---------------------------------------|
| Action:       | Combine the Parts                     |
| Prerequisite: | The values of all the Parts are known |
| Consequence:  | The value of the Whole is known       |

## FIND-PART

|               |                                                                 |
|---------------|-----------------------------------------------------------------|
| Action:       | Separate the known Parts from the Whole                         |
| Prerequisite: | The values of the Whole and all but Part <sub>n</sub> are known |
| Consequence:  | The value of Part <sub>n</sub> is known                         |

ments for inferring the effects of qualitative changes in circuit values (e.g., "If a Part increases, and all the other Parts stay the same, then the Whole increases").

relevant to the current problem situation whenever the consequence of its action matches the current goal.

During problem solving, Model(2) applies its schematizing productions to represent explicitly the Whole-Parts relations between the quantities involved in its problem solutions, as shown in Figure 1. The figure shows the Model(2)'s final representation of the problem about a series circuit with two resistors,  $R_1$  and  $R_2$ . The values of the total voltage ( $E_T$ ), total current ( $I_T$ ), and the resistance at  $R_2$  were given, and the task was to solve for the voltage drop across  $R_1$  (i.e.,  $E_{R1}$ ).

Model(2)'s representation consists of three main clusters of nodes and links that are organized hierarchically to represent different levels of circuit relations. The node  $S_{Req}$  is an equivalent resistor that represents the series relation between  $R_1$  and  $R_2$ . The values of known quantities are included in the representation as quantity nodes identified as properties of  $S_{Req}$ ,  $R_1$ , and  $R_2$ . Each quantity has an identity (indicated by the "id" link) and an amount ("amt"), e.g., the quantity  $I_{Req}$  has an amount 2 A,  $E_{Req}$  has an amount 60 V, and the resistance at  $R_2$  is 10  $\Omega$ . Furthermore, the whole-parts relations between the quantities are made explicit.  $E_{R2}$  is represented both as a Whole that results from the multiplicative combination of the Parts  $I_{R2}$  and  $R_2$ , and as a Part of the additive combination involving the Whole  $E_T$  and the other Part  $E_{R1}$ . The current through  $R_2$  is constrained by the multiplicative relation with  $E_{R2}$  and is also constrained by the total current through direct identification.

The relations between the quantities in Model(2)'s problem representations reflect three important characteristics of what it means to solve a problem with understanding. The representation is *coherent* in that it preserves an integrated trace of the inferences from the separate solution steps and shows how these separate inferences serve to mutually constrain each other. For example, the model understands that the voltage drop across  $R_2$  is constrained to be a Whole that results from the multiplicative combination of  $I_{R2}$  and  $R_2$ , and a Part of the additive combination involving the total voltage and the voltage drop across  $R_1$ ; the current through  $R_2$  is constrained by the multiplicative relation with  $E_{R2}$  and is also constrained by the total current through direct identification.

Its representation *corresponds* to the quantitative structure of the domain as defined by the integrated networks of simultaneous constraints. Finally, its representation is *connected* to the model's general knowledge of quantitative relations embodied in its Whole-Parts schema. Procedural attachment associated with the Whole-Parts schema can operate directly on the objects in the model's problem representation. There is no necessary intervening step of translating quantities into formulas, and no separation between solving for a value and representing that value in the model's problem representation. Not only is this an efficient

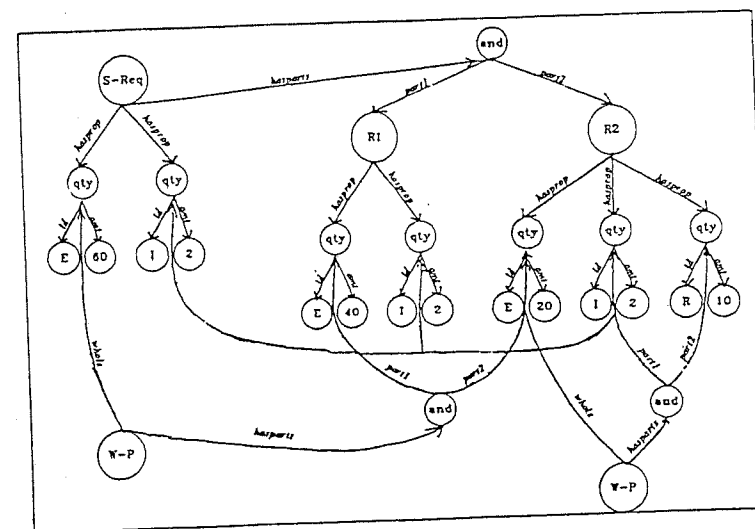
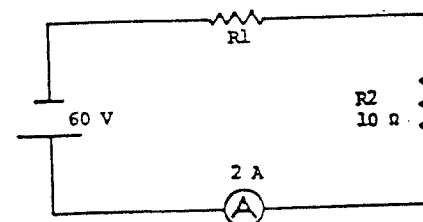


Figure 1. Model(2)'s final representation of a problem about a series circuit.

solution, but fewer steps allow fewer chances for error, especially as problem complexity increases. Also, the redundancy in Model(2)'s problem representation simultaneously constrains the individual circuit relations and therefore should lead to reliable performance by acting as structures for blocking errors that commonly occur. Redundancy should also provide some robustness against forgetting. Finally, the structural relations in Model(2)'s representation should enhance learning by enabling the model to recognize the structural similarity between problems involving DC circuits as well as transferring the concept of simultaneous constraints to AC circuits.

In contrast to Model(2), Model(1) lacks procedures for directly representing the quantitative relations between circuit quantities. The model's knowledge of circuit relations is restricted to a set of separate formulas and rules, with no way of understanding the relations between them, as shown in Figure 2. Quantities are represented as attributes of resistors, but there is no *coherent* structure of quantitative relations between those quantities. Model(1)'s problem representation does not directly *correspond* to the structure of the domain and is not directly *connected* to its general knowledge of quantitative combinations. The objects in Model(1)'s problem representation are quantities identified as properties of resistors. However the arguments to the Whole-Parts procedures are objects identified as wholes and parts. Therefore the Whole-Parts procedures cannot operate directly on these quantities to infer additional relations, but instead must be mediated by circuit formulas. Model(1)'s Whole-Parts schema is used only to select appropriate operations to solve equations quite independently of the model's problem representation and understanding of circuit relations. This is a less efficient solution than Model(2)'s and increases the probability of error as problems become more complex. Furthermore, the lack of redundancy in Model(1)'s problem representation makes it less likely that the model would detect errors when they do occur, leading to less reliable performance. Finally, Model(1)'s problem representation only includes information about hierarchical relationships between resistors and associated quantities and therefore provides no basis for transferring understanding of D-C circuit relations to understand A-C circuits.

### 3.0 Discussion

In summary, two models of solving D-C circuit problems have been described. The models differ in their ability to represent relations between circuit quantities in ways that are proposed to reflect important difference in their understanding. It is also proposed that the knowledge included in Model(2) constitutes a more adequate basis for performance and learning than does the knowledge included in Model(1).

Gestalt and educational psychologists also argued that the effectiveness of instruction for

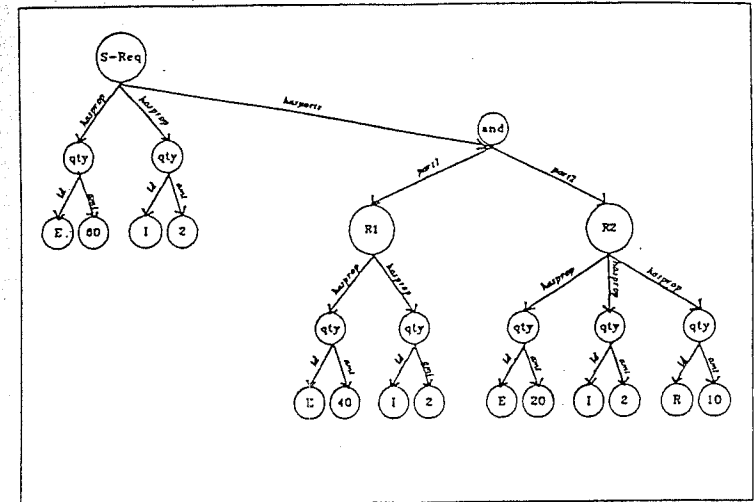


Figure 2. Model(1)'s final representation of a problem about a series circuit.

problem-solving performance and later learning depends in large part upon whether students acquire an understanding of important structural relations between the elements in a domain. The analysis presented here goes beyond earlier descriptions of the effects of understanding to provide a specific hypothesis about the cognitive structures and processes that constitute that understanding. In the analysis, the hypothesis concerned how knowledge of general part-whole relations could be applied to achieve structural understanding of simple circuits. Of course, confirmation of this hypothesis requires further empirical and theoretical work. In the meantime, support for its general properties comes from the work on teaching children subtraction discussed above, and from recent formal analyses of the role of general concepts in learning a geometry and arithmetic syntax (Greeno, 1983; Resnick, 1983).

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#### The Clinical Interview :

##### A Tool for Investigating Student Knowledge and Ideas

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Introduction: Clinical Interviewing has become increasingly attractive to researchers of student knowledge and student approaches to problem solving. This attraction is probably related to its potential for producing data which is investigator-bias-free. Referencing sample data from two actual interviews, this paper reviews those issues which are of concern to investigators who use this method or theoreticians who use interview data in their model building. Comparisons between The Clinical Research Interview and other research techniques are summarized in Easley (1977) and will thus not be discussed.

After moving through the usual project decision steps relating to topic, study population, and general questions to be asked, the clinical interviewer's first difficult task is the formulation of an opening question to be asked of the subject. The significance of the opening question lies with the fact that research interviews, unlike other investigative tools, often either deal with only one question or have their entire structure based on one question.

I consider the phrase degree of suggestiveness appropriate to use as a first order separator of question types. Planners of interviews devote a lot of time and energy devising questions, particularly opening questions, to be as non-suggestive as the project goals allow. After questions have been formulated, the matter to consider next is that of interviewer intervention. That is, to what extent can the interviewer interact with the subject. Most Clinicians are willing to intervene in some way, but it must be done in such a way that ensuing data is meaningful from a cognitive science standpoint. There certainly are other issues but the two just cited are clearly important ones and will be the focus of this paper.

Structuring Appropriately-Worded Questions: Examine the opening question providing the basis for Protocol I which makes up figure 1; it is given in the parentheses at the beginning. Does it look like a reasonable question to use? How ought it be rated in terms of its "suggestiveness"?

PROTOCOL I

(The subject is handed a piece of paper on which this problem is written: "An object starts from rest at  $t = 0$ . Its velocity is given by  $v = 2.5t$ . What is the acceleration?" He is asked to read it aloud).

01. S: ...and its velocity is given by  $v = 2.5t$ , what is its acceleration...ok so you know  $v = 2.5t$  (writes down  $v = 2.5t$  on paper) and you want to find out 'a' (writes  $a = ?$ )...wait a minute...2 point...that's just a ratio (questioning tone).
02. I: No, that's an equation describing the velocity.
03. (Long pause while subject looks down on paper).
04. S: Velocity is  $2\frac{1}{2}$  times  $t$ .
05. I: Right.
06. (Subject moves eye attention back and forth between paper on which problem is written and sheet of paper on which work on problem is being done; taps on paper). Ok..um..what I would do now is just try to figure out the equation that we can get these numbers to fit into so that we can solve for 'a'.
07. I: Alright.
08. S: (Writes the following on paper and says aloud). So I think it's 'v' is equal to 'a t'....solve for 'a' is equal to...'v' over to 't'...then if you know 'v' is '2.5t'...put 'v' over '2.5t'...Ok, that's just ratio...then you could plug any numbers in and then we...but no matter if you put any number in there then it's going to be different...than this fraction (referring to  $v/2.5t$ ) would turn out differently....

-Figure 1-

Consider the phrase, "... Its velocity is given by  $v=2.5t$ ..." Compare that statement to another version which might read "Its velocity in meters/second is given by the equation  $v=2.5t$ , when 't' is measured in seconds". The addition of units and the word "equation" might be considered "hints" or suggestions about the interpretation of the question which might preclude student ideas like the one expressed by the student where he says: "Is that a ratio?". One would therefore describe the second version as being more suggestive than the first. The interviewer's response recorded in the next line ("No, that's an equation") stands as an example of interviewer intervention considered inappropriate by virtually all researchers.

In his earliest writing, Jean Piaget, considered by many to be the archtype clinical interviewer tells us:

"It is so hard not to talk too much when questioning a child, especially for a pedagogue! It is so hard not to be suggestive... When students begin they either suggest to the child all they hope to find out or they suggest nothing at all."

Jean Piaget, The Child's Conception of the World. p.9

Since one of the main advantages of the clinical interview is that it serves as a mechanism which at least permits non-standard or non-anticipated responses, questions and interviewer interventions must be carefully planned to allow for them. I feel obliged to point out, parenthetically, that such a possibility is less likely with the frequently-used multiple-choice response questionnaire.

Interviewer Practices Following Presentation of Opening Question:

The interviewer comment in line 02 turned out to be a statement which made the original question more suggestive than intended. There are few guidelines for the interviewer to follow upon reaching the point where the subject ends his response to a particular question. Love (1970) believes that the first line of action should be no action at all - to simply neither say anything nor do anything and to leave formal termination of the interview to the subject. This is obviously the most non-suggestive follow-up to any question.

It may be that much of the concern over interviewer-responses which may be in the least bit "suggestive" is related to the Piagetian method of investigating cognitive processes. In Piaget (1929), one finds

continued reference to what that author has labeled "Liberated Convictions" and "Suggested Convictions". Liberated Convictions are those ideas which are developed as such within the mind of the subject and which are then merely freed by the interviewer. Suggested Convictions are ideas which may be tied to the influence of the interviewer; it may be that the subject had either no preconceived idea of the question or a preconceived idea which he did not wish to share and was therefore simply saying something to satisfy the interviewer's need for a response. Notice the emphasis of the word "may".

Whatever other plans the interviewer may have about responding to the subject, he must be prepared for the possibility that the subject might simply stare back at him after the opening presentation. If the subject doesn't respond at all or reacts in such a way so as to indicate that he does not understand the question, the first reasonable line of action is to simply repeat the question with a slightly different tonal inflection. This is a subtle way of inferring that the question has been rephrased and that the subject ought to be able to respond to this "new" question.

Continuing with our consideration of appropriate interviewer follow-up actions, there is no consensus on what might constitute the next level of interviewer intervention; the suggestions which follow are roughly equivalent to each other.

To begin with, one may actually rephrase the original question. Interviewers working under the Piagetian guidelines as summarized in Oppen (1977) are permitted to do this. Rephrasing often requires its own set of guidelines. For example, the word "array" was carefully chosen by me for use in questions about electrical activity in various arrangements of batteries, wires and electrical resistors. If I felt that I ought to rephrase this question, I would not have used "circuit" in place of "array" because "circuit" implies that electrical activity in the magnitude of that found in familiar "circuits" existed in that particular arrangement. I might have used "collection" or "arrangement".

Once the subject begins to respond, most feel that the safest intervention is to nod one's head or to say "uh huh" — one finds protocol records filled with interviewer "uh huh"'s or other parallel phrases which generally translate to "Go on — I'm following you".

The people working on information processing models from interview protocols at Carnegie-Mellon restrict their interviewers to only one response: "Please think out loud." Ericsson and Simon (1979) report that there is adequate evidence to support the thesis that the CMU prescribed interview technique has no effect on the cognitive processing being investigated. I haven't seen any reports of research on the effects of other interviewer interventions, but the frequent appearance of "uh huh" can be taken as tacit evidence of its being considered to have little or no influence on the data.

What other possibilities are there? One response which stands a good chance of being non-influencing is that in which the interviewer merely repeats the interviewee's remarks verbatim with the addition of a prefacing remark such as, "You say that...". When carried out appropriately, Benjamin (1969) sees it as having a positive effect on the flow of interaction between two people. He suggests that such an action tells the subject that the interviewer is paying such close attention to what is being said, that he can repeat it word for word. Most of us consider it quite a compliment that another person holds what we are saying in such high regard.

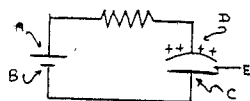
Line 07 of Protocol II (see figure 2a) demonstrates the use of repetition of part of a subject's response. Partial repetition is not quite the same as total repetition but, if restricted to the subject's last words or actions, the effect should not be significantly different. In this case, the response consisted of a verbal description of the subject's actions added to the last phrase uttered. Judging from the part of the protocol which follows this response, the effect of this particular action appears to be of the non-intervening variety.

As best as can be determined from personal recall, line 13 was not meant to be a synthesis of what had gone on, but the record does show this to be the case. In retrospect, I should have said, "So you thought the current had to have a continuous flow..." This last version would have fallen within Benjamin's guidelines.

Protocol II: Probing as a Follow-up Action: This protocol includes a line of intervention which is representative of a completely different tack in interviewing and that is intervention to test a particular

## Protocol II

05. I: Why don't you give me a sketch of the problem over here.
06. S: It looks like - this is a circuit (draws circuit diagram shown directly below), and there's the (inaudible) and here's the capacitor - and usually there's a resistor - and one thing that I'm confused on is why you have to have a resistor; another thing I was confused on is how, like, I understand how the excess charge gets here (points to (C)), but I have no idea how the excess charge got on that side (points to part of circuit between (D) and (A)). I asked Professor (name) in class but I just couldn't see, I knew the charge couldn't go through it (the capacitor), but I had this big argument with a friend to see whether the current went here (C) and then went here (D) or went through it.



(Letter Labels added by investigator)

07. I: In other words, that when you were talking with your friend you thought that maybe the current flowed to this side of the capacitor (C) from this side of the battery (B)?
08. S: Yeah, and then the others to here (points to (D)).
09. I: Uh huh. And what's wrong with that?
10. S: It just doesn't seem right.
11. I: Why?
12. S: I just don't think the whole current could go in two different directions. The current had to have one continuous flow, it couldn't, couldn't, just wouldn't have a circuit, it wouldn't be - it would just kinda stop here.

-Figure 2a-

## Protocol II (cont)

13. I: Uh huh. So, I mean because it wasn't a continuous flow, you -
14. S: It didn't seem right.
15. I: It didn't seem right? So then how did you modify that to get to this (referring to charged capacitor)?
16. S: I didn't (laughs). I just asked the Professor.
17. I: And so what kind of answer did you get that -
18. S: Oh, it was a good answer. He told me that, ah, excess negative would be on this side (points to (C)) meaning more charge would go here, and then - therefore you, he explained that it was a billiard effect, like a little green charge goes here (still referring to (C) and the electric field, and in other words, there's yellow ones here (pointing to (D)) and it makes the yellow one want to move here. It's not that the green one is going to go through the capacitor, it's just that the green one is going to make a yellow move up an electric field.
19. I: I'm a little bit -
20. S: This is like an electron (back to point (C)) -
21. I: Okay
22. S: And then that electron is going to cause a field in the capacitor.
23. I: Uh, huh.
24. S: And now it's going to make this electron (at point (D)) move away because of the field and therefore this is going to be a net positive (at point (D)).

-Figure 2b-



hypothesis. Such follow-up action is one form of an intervention called "probing". Here, probing questions are used to delve into aspects of subject responses which the interviewer has judged to be of interest. Protocol II was prepared from the third interview held with this subject. Before this interview took place, a review of the protocols from the first two interviews led the investigator to believe that this person held an interesting mental model about electric current. The problem was to find a way to elicit this person's model; the resolution required finding a way to do it so the results would be judged to be "liberating" rather than "suggestive".

In this case, the investigator had only tentative evidence that this person's model did not match those held by the investigating team. It is quite possible that the model reported in line 18 of Protocol II (figure 2b) might never have been made known to the investigator without the introduction of the probing question of line 17. This particular probing question seems to have merely liberated the subject's model. The judgment about liberation as opposed to suggestion is based on an examination of the specificity of the description - the terms appearing in this line do not seem to be tied to anything previously said by either person.

Probing doesn't always produce such clear results. Consider line 09 (still Protocol II but figure 2a), "Uh, huh, and what's wrong with that?" Here the interviewer made the judgment that the subject had some difficulty reconciling two ideas as presented to her from other sources. The evidence suggesting that a difficulty exists is found in line 06 where the subject said, "...I just couldn't see..." On the other hand, subject responses in lines 10 and 12 indicate that the contradiction hypothesized by the interviewer probably didn't even exist in the subject's mind until a possibility was suggested.

The decision to use the first probe (i.e., the question found on line 17 of Protocol II) was based on a reasonably careful consideration of evidence. In the case of the second probe, it was extended on the basis of a fleeting remark made just seconds before the decision to use it was made. Piaget's comment that it takes at least a year of daily exposure to develop appropriate interview skills probably relates more to the development of judgment in the use of probes than any other aspect

of interviewing.

Probing questions are often worked into the interview through the use of a mechanism called a "Counter-Suggestion".

An example of this application would be the following:

"When I was talking to a person enrolled in the same physics course as you are, this person said...."

This kind of interviewer-remark often provokes the subject into further expanding some previously-made statement. Since no specific mention is made to the contrary, the subject probably assumes this other person to be of the same level of understanding as he is. Peers are normally considered not to be authorities, no matter how capable they are. Unfortunately, neither Protocol I nor Protocol II contain examples of the appropriate use of counter-suggestion. It should not be too difficult to imagine that, deployed at the right time and place, counter-suggestions can be especially valuable in the testing of how firmly someone believes in an idea - sometimes called "cognitive resiliency".

Summary and Conclusions: The main thrust of this paper has been to demonstrate that research interviews involve more than a "let's sit down and chat" operation.

The wording and structure of questions used in research interviews must be carefully considered. The best questions are those which encourage responses which are appropriate to the research interest but which do not preclude those responses which, though found appropriate when retrospectively examined, were never considered among the possible ones by the researchers.

That the interviewer must interact with the subject as little as he possibly can has grown out of several years of attempting to evaluate results of experiments designed to investigate the nature of human thought processes. Probing, as described here, ought not be hastily introduced into an interview. When attempted at all, it is safer to do it only when the interviewee has ceased making spontaneous remarks. Even then, the interviewer should wait until some time has elapsed during which there has been no response. This guiding philosophy comes from accepted scientific experimental practice: measuring instruments should

offer as little disturbance to the system being measured as possible. To some extent, the problem is akin to the measurement of a person's waist for the purpose of selecting a pair of trousers. Surely many of us find it difficult not to reduce our waist circumference as the clothing store salesperson places a tape around that part of the anatomy. Conservatism in the use of probes is also consistent with the Piagetian concern over the difference between Liberated Convictions and Suggested Convictions. It goes without saying that every investigator would like to point to a subject's revealing response and pronounce it "truly liberated"!

In spite of all of the caveats given here about probing questions, it is my contention that there is a place in Clinical Interviews for questions designed to investigate subject ideas and to test hypotheses. - in fact, I find the resulting data to be the most interesting of all interview data.

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#### AN EXAMPLE OF THE SPEAKING-ALoud TECHNIQUE IN THE DOMAIN OF ELECTRICITY

Walter JUNG

1. In the following I give the structure of a speaking-aloud session and my interpretative comments. The speaker is a student of rather high qualification. He has made his Diplom in Physics with good marks, and he is interested in teaching so that he wants to become a teacher. Thus he knows a lot of highly technical details. But, as will be seen in the sequel, he gets into serious trouble when confronted with a relatively elementary problem. Every academic teacher knows quite well that this frequently happens. It is an interesting, and so far not analyzed, fact that one can be a good working physicist without having a complete grasp of some fundamental concepts.

2. I should like to refrain from giving more than one example of a speaking-aloud session, and, as I said, I try to make the structure of the approach of that student visible. Of course, this is a highly interpretative attempt. But this may prove more fruitful in this context than giving a word-for-word translation of what could be got from the tape recording, which would be no less interpretative.

The problem is given on a sheet with a diagram as follows:

A circular wire is positioned as shown in the figure in a magnetic field with  $\vec{\Phi} = \text{const. and } \neq 0$ . One half of the ring consists of a wire with resistance  $R_1$ , the other half of a wire with resistance  $R_2 \neq R_1$ . Both halves are connected in points 1 and 2.

- Does a voltage (Spannung) exist between 1 and 2?
- How could this be measured?

3. Now I give the student's responses, as given by the tape recording of what he says, and by notes and diagrams he has jotted down during the session:

- (1) Firstly, he analyses the task: What is given? What is  $\Phi$ ,  $\dot{\Phi}$ ? What is asked for?
- (2) He mentions "voltage" ("Spannung"), but there is never any questioning of what that means and to what it refers.
- (3) Now comes a decisive phase: The student taps his knowledge about induction and retrieves what he thinks is the relevant scheme. He says, "by a magnetic field ... a current is induced." (I) From the point of physics this is a weak scheme. But it mirrors what frequently is the first introduction of induction phenomena.
- (4) In the next period he elaborates on this scheme, stating that this induced current is proportional to  $d\Phi/dt$ . He hesitates, repeats what he has already said. Obviously he is searching for a gate allowing to pass from the scheme to the problem data.
- (5) Finally he seems to see one, stating that "the current generates voltages with several resistances" (II).
- (6) In order to capitalize upon this link he must know more about the current. Thus he says, "because  $d\Phi/dt$  is constant the current is constant, too." (III). This link is weak in itself, though the constancy of  $I$  is correct. (Also, he seems to think of the constancy in time and everywhere at once. At least, he never questions the constancy of  $I$  in the two halves.) He fails to ask for the mechanism by which the induced current arises. He tries to find something to say about the voltages, and a new scheme is retrieved:

"the sum of the voltage drops must be zero taken over the whole circuit" (IV).

Now the stage is already set for a conflict, as can be seen from what he says after a longer pause - during which he may be working within his mind, unable to verbalize what is happening there. What must have happened is, that he tried to see some connection between: the current is constant, the current generates a voltage (drop), the sum of the voltage drops is zero. He states the following scheme which explicates the relation between current and voltage drops:

- (7) "Over the part  $R_1$  the voltage drop is  $R_1 I$ " (V), and similarly for  $R_2$  he states " $U_2 = R_2 I$ ". One can now easily see why the conflict arises. By scheme (IV) is implied that "voltage" or "voltage drop" is "potential difference". But  $I \cdot R$  is not identical in meaning with potential difference. (Later, in a discussion after the session, he explicitly states that  $IR$  is "the usual meaning of voltage (Spannung)".)
- (8) In the next step he realizes the conflict himself as can be seen from what he jotted down upon the sheet of paper. Explicitly he states that "there is a problem with the sign" (of the voltages). The problem is that the sum of the  $IR$ 's is not zero. At that point he could have noted that the  $IR$ 's are not potential drops. But he does not hit upon this consequence. In fact, he arrives at the difference  $U_2 - U_1$ , which is still not zero. How does he arrive at the difference instead of the sum? This is difficult to understand. One explanation is that he tries to meet the condition, sum of drops zero, and therefore is eager to come as near as possible to this aim. Thus he begins at point 1 with a common potential (zero) for both "drops" and moves to 2 for both in the same

direction. Thus in junction 2 he has a potential jump of  $U_2 - U_1$  ( $R_2 > R_1$ ). In the following he distributes this jump equally between the two junctions. He finds a voltage of  $\frac{U_2 - U_1}{2}$  in each junction.

How, under these circumstances, a stationary current could be possible, is not discussed and presumably not thought of. In an earlier phase he obviously used the correct signs of the voltages  $U_1$ ,  $U_2$ , and consequently he inserted into the two junctions voltages  $-\frac{U_1 + U_2}{2}$ . This can only be seen from what he jotted down. It is not in his talk.

- (9) Localizing the voltages between the contact faces of the two half circles, makes sense to him because he notes that at these points "the resistance changes all at a sudden, though the current stays constant."

It is obvious that he has a stable meaning of "voltage drop", i.e.  $I R$ , but no stable reference, a correct one being, e.g., the ordered pair of end points of the piece of wire.

His last explanation shows that he changes the reference of "resistance" to be a local entity. It is something which "the" current suddenly faces, at the junction. He does not say so explicitly, but one can easily imagine that he has the following mechanism before his mind's eye: "the" current is leaving resistance  $R_1$  ( $< R_2$ ), faced with bigger resistance at the beginning of  $R_2$  and so needs an extra push at that point, and only there. This move can be seen as an example of "local reasoning" (Viennot). Now, local reasoning is quite appropriate in this case: The fundamental equation  $\vec{j} = \sigma \cdot \vec{E}$  is a "local" equation. The student correctly tries to reconstruct the mechanism by which the current stays constant. And mechanisms usually are local affairs. But he seems to lose sight of the chaining of mechanisms, e.g. the effect of local charge accumulations upon other parts

of the circuit. We can see here a defect in strategies, too, e.g. control processes (cf. Brown-DeLoache 1978). Thus he could have stopped in order to ask himself: Is this the complete mechanism (cf. de Kleer-Brown 1981). One reason why he does not do so can only be inferred from what he says: He seems to think that in the parts different from the junctions there is no need of an extra push because induction alone moves "the" current on there.

In fact, at this stage he invokes a new scheme which, in view of what follows in (11), lends some plausibility to the aforementioned hypothesis. He says, "the(!) current follows the electric field" (VI).

This is the first time he mentions the field. The field is one of the main instruments in physics of chaining mechanisms, because it is thought of as a continuous whole of local, even pointwise, activating properties.

- (10) He tries to capitalize on this new idea, pondering a rather long period in silence, then repeating what he has said about the voltage drops at the junctions. Again there is a long silence from which he comes out with a reference to the electric field, "how about this electric field?"

- (11) After so many moves, now he links the electric field explicitly with the induction process, referring to Maxwell's equations (VII), and stating that the field is "circular" and "equal". It is obvious what he has in mind.

Then he goes on to the "voltages", which "depend upon that piece (of the circuit) which is under scrutiny." But he does not succeed in making progress. He repeats what he has already said, always thinking of  $I R$  as potential difference.

(12) He seems to be sure now, that in the junctions there are voltages. Going over to the question how to measure the voltage between 1 and 2 must lead to difficulties, and he says so: "the question is somewhat unclear." This leads him back to the first question. He does not feel satisfied with his solution, and he resumes thinking of the first question by asking what is the "distribution of the field". Then he produced a new idea, what "if I would open the circuit." He thinks of the two parts in separation, in each there is a current, each has a voltage drop  $U_1$ ,  $U_2$  respectively - what happens "if I bring the two halves together?" His answer comes without hesitation: "there (at the junctions) arise contact voltages." After a long silence he comes out with a rather detailed local mechanism, "electrons are coming through the greater resistance - that means - suddenly ... charges are (retarded and) accumulated and a voltage arises" (the German is much more concrete, the voltage is "built-up"). But again he stops short of completing the mechanism. Beginning with the idea of equal currents in both separated parts, he should have asked why on earth the currents in the parts should be equal if they interact with the induced field only, and not with each other. In any case, he comes very near to one possible solution by analyzing the adaptive, transient mechanism which renders the current in the two parts equal. He again wanders off to the second question of how to measure the voltage.

(13) But he is still annoyed at something. After a very long silence he says, "somewhere I make a fundamental mistake - it is not quite logical". After a long silence again, he asks himself, "what happens in the wire - the field and a force on the charge - which leads - to a current - but the two wires have

different resistances - so we need compensating voltages to be built-up till this counter-voltage is just of the right value to balance the issue." (Note the lack of precision in reference: to what does this issue - "Sache" in German - refer? To "the" current, to current densities, to resistances, to wires, junctions?) After a longer pause he adds, "and then we have a constant current everywhere." This is a progress, because now he does not seem to start from equal currents in the two parts. The solution would be quite near at hand, if only he could discriminate between the electromotive force represented by the induced electric field, and the electrostatic field which arises from the accumulation of charges at the junctions (which is still a bit too simple) and which equalizes the two currents.

Instead he falls back on  $I R$  as voltage drop along the resistance, in addition to the voltages in the junctions. In fact,  $I \cdot R$  is the electromotive force plus potential difference. Till the end - he gives up shortly after the last remarks - he tries to insert voltages in the junctions such that the sum of all voltage drops is zero.

Now, what could be learned from exercises of this sort?

- (1) Something about the limitations of the technique. It has been used in Germany in psychological research at the beginning of this century, and abandoned because of its limitations (I am told, cf. also Bower 1978, p.359f.). The technique has been revived recently in research on problem solving (in Germany e.g. by Dörner, in USA by Simon & Simon 1978, and others), and reading articles about it gives a positive impression. Comparing the type of problems used by Dörner (Boolean algebra) or by Simon (problems in elementary mechanics) with the problems I have used (the induction

problem as illustrated here, tasks from elementary optics in other cases) shows a marked difference: In the former case there is always the organization of a class of formulas in the foreground, and in my case all depends on getting clear on a qualitative representation of the task, which gives meaning to the formulas. In addition, in the induction problem there are only very few formulas which can be used. Now, in this case the limitations become evident. There are not only frequently utterances which cannot be understood, there are many periods of long silence. And it would be rash to suppose that the proband does not think during these periods, or that he forgets to verbalize what he thinks.

I have tried the technique by myself, and I have found that at times I am simply unable to state what happens in my mind. There are processes of envisioning, e.g., and trying to verbalize what is going on would stop that process. Results emerge, which in turn can be verbalized. Often they seem to be decisive new approaches. One can only try to find out from hindsight what happened, by introspection and questioning later on. In fact, in my trials each session was followed by a long discussion session, immediately after the student has finished his problem. A look at his written notes and some quick questions usually reveal his main solution moves very soon, and a discussion can be started. If the speaking-aloud technique is used with tasks of the type I have used, I should like to recommend this after-session procedure.

- (2) Results of the analysis of trials done so far can be summarized under two headings, first, physics knowledge, second, problem solving strategies.

(i) I have tried to construct a list of ideal solution

paths. But it is not necessary to discuss it in this context. What is found is the immediate retrieval of formulas:  $U = I \cdot R$  and  $U_i = -d\phi/dt$ . The main difficulty which prevents the successful solution of the problem has already been mentioned: There is a remarkable lack of meaning differentiation concerning  $U$  in both formulas. The terms "voltage", "voltage drop", "potential difference" are all used without clear-cut meaning differences. The term "electromotive force" (variously termed "EMK", "Urspannung", "Quellenspannung" in German text books) is not mentioned. If one tries to solve question (a) formally, which is one of the possible approaches, it is absolutely necessary to have these meaning differences and the respective references in mind. From what has been observed so far, it must be concluded that this is not sufficiently learned. For instance, one approach to avoid the misleading term EMF in textbooks is to introduce the term "source voltage" ("Quellenspannung"), which means "potential difference between the terminals of a source without load". Clearly this concept is difficult to apply to a ring, which has no terminals.

Invoking electric fields, dynamic and static ones, is an approach which leads to a solution without any use of the voltage concept except in the sense of potential difference. This approach has been observed once, and the person asked was a Professor with a training as an engineer. But, as I said, I do not want to discuss the approaches systematically, nor is the number of persons asked high enough to justify a statistical analysis.

(ii) Concerning the second issue, strategies, it is important to note that the usual pair working-forward vs working-backward does not easily apply. The reason seems to me the same as in the first issue, problem

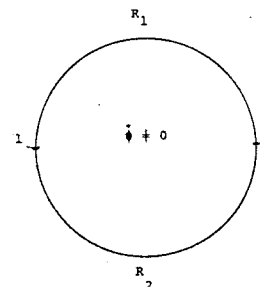
type. These strategies are observed when the solution requires organizing a set of equations, such that finally the value of the variable in question emerges from the chain. This is not the case here. The available formulas do not normally contain the variable asked for (potential difference between 1 and 2), it must be constructed from the available formulas. Moreover, the problem does, in fact, not ask for a value. It simply asks, yes or no. The first step in any solution is an elaboration of the meaning of the question. In this sense backward-working seems necessary. Of course, one may begin by writing down formulas which seem relevant, and do some calculations. (In fact, the data are very general such that only functions can be calculated, no values whatever.) If the solution emerges, depends upon the availability of a correct understanding of IR. Normally all that is arrived at may be  $U_1 = IR_1 + IR_2$ , which in itself does not help to give the answer.

Forward-working may be conceived in the following way: One tries to understand what happens in the induction process. This leads to qualitative steps of reasoning: a constant electric field is induced, which is not curl-free, and which would lead, by reason of symmetry, to currents of different intensities in the two ring halves - by what sort of mechanism can the intensity of currents rendered equal in both halves? This leads to the idea of charge accumulation, which means charge separation, which means building-up a curl-free electrostatic field. Now the answer "yes" is at hand. In a way, this is forward-working, because all this reasoning and questioning can be done without ever thinking of the original problem. Thus I think that analyzing problems of this type may lead to reconsidering the strategies mentioned.

One more, and rather strong, impression concerns the vital topic of control processes. Researchers are inclined to think that these meta-cognitive capacities are essential for a good problem solving ability (cf. e.g. Chi et al. 1982, Brown-DeLoache 1978). The strong impression I got in my speaking-aloud trials refers to age groups: Though the physics students were poor in answering the problem, yet they exhibited in a much higher degree control processes than younger students; they came back to the question already answered; they asked, could that be, and said, let me look at this again. From the point of view of a scientific education this would be a very satisfactory result if it could be widely confirmed.

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$$\dot{\phi} = B \cdot A$$

$$\dot{\phi} = \frac{d\phi}{dt}$$

Note: I owe the problem in this version to F. REIF.

## CATEGORY QUESTIONNAIRES - THE TECHNIQUE AND SOME RESULTS

Walter Jung

### 1. Introduction

A C-Questionnaire asks for subsuming a concept under a very general category. The idea behind the development of this instrument is the observation that often physics concepts belong to different categories from those of the respective common sense concept. For example, "light" in physics is a process (propagating waves, for instance), but the naive meaning of "light" is a property of surfaces, or a condition by which sight is possible, etc. Also it is hypothesized that by discussing categories with students, they may come to see the necessity of restructuring the meaning of concept-words when used within the context of physics. Therefore C-Questionnaires are hoped to be of diagnostic and of didactic value.

The instrument is far from perfectly developed. But work so far seems to me promising such that further refinements seem to be rewarding.

### 2. The C-Questionnaire

The first and so far mainly used format required the decision into which list a given concept-word should be included (see Appendix for the original questionnaire). Three lists are exemplified (more could be and have been given):

- List 1 contains things that occur (events, happenings, processes, like going, chewing, boxing)
- List 2 contains things that endure (material objects like stones, chairs, books, molecules, in short, "substances")
- List 3 contains things that recur<sup>1</sup> (in this case properties like thick or thin, hard or soft, magnetic)

Then a list of concept-words follows which are to be numbered according to the list-number which seems appropriate. Students also could open new lists if they found it necessary. It should be noted, that there is no uniquely correct answer, not even incorrect ones. The student only exhibits by his decision what aspect is prominent in his mind.



Concerning elementary electricity, the following concept-words are proposed: electric current, voltage, electric charge, electron, energy.

Other formats have been proposed and are used in trials.

### 3. Some Grade Comparisons

Results are given in rounded percentages. I compare samples of grade 8 (N=70) and grade 10 (N=73).

In cases where I give the choices of the list-numbers only, the sum of percentages is not always 100. The differences are generally small.

Categories: 1=event, 2=substance, 3=property, 4=no answer

#### 3.1 Current

|       |  | Category |     |     |
|-------|--|----------|-----|-----|
| grade |  | 1        | 2   | 3   |
| 8     |  | 30%      | 50% | 20% |
| 10    |  | 25%      | 68% | 7%  |

A chi-square test exhibits a significant difference between the categorization distributions ( $p < 5\%$ ).

#### 3.2 Voltage

|       |  | Category |     |     |
|-------|--|----------|-----|-----|
| grade |  | 1        | 2   | 3   |
| 8     |  | 49%      | 26% | 19% |
| 10    |  | 21%      | 32% | 40% |

Again a chi-square test reveals a significant difference between the two samples ( $p < 0,1\%$ ).

#### 3.3 Charge

|       |  | Category |     |     |     |
|-------|--|----------|-----|-----|-----|
| grade |  | 1        | 2   | 3   | 4   |
| 8     |  | 30%      | 14% | 9%  | 47% |
| 10    |  | 18%      | 22% | 51% | 7%  |

Again a chi-square test makes it very highly improbable that the two samples are drawn from the same population ( $p < 0,1\%$ ).

#### 3.4 Energy

|       |  | Category |     |     |
|-------|--|----------|-----|-----|
| grade |  | 1        | 2   | 3   |
| 8     |  | 30%      | 30% | 37% |
| 10    |  | 21%      | 38% | 37% |

This time the difference is not significant.

#### 3.5 Electron

It may be of some interest to see an example of a very "sharp" categorization distribution in a group. The grade 10 sample exhibited the following choices for the concept-word "electron":

|       |  | Category |     |    |
|-------|--|----------|-----|----|
| grade |  | 1        | 2   | 3  |
| 10    |  | 0%       | 95% | 4% |

(Choices for grade 8 are not available.)

### 4. Some Concept-word Comparisons

I confine myself to the grade 10 sample. Comparing 3.3 with 3.5 shows an obvious difference in categorization which is not in need of further statistics. In other cases the differences are less salient. I take some interesting pairs.

#### 4.1 Current and Energy

A chi-square test reveals a very significant difference between the categorization distributions of the two concepts in this sample ( $p < 0,1\%$ ).

The reason is revealed from inspection of tables 3.1 and 3.4: Energy is categorized equally often as "substance" and as "property", not so current.

#### 4.2 Current and Voltage

Again a chi-square test reveals a very different categorization pattern in the grade 10 sample ( $p < 0,1\%$ ). The reason is that voltage is often categorized as a property, not so current.

### 4.3 Voltage and Energy

It does not come as a surprise that voltage and energy exhibit no significant difference of the categorization pattern according to a chi-square test. There is a small bias in favour of "property" for voltage, in contradistinction to energy. But the difference is not significant.<sup>2</sup>

### 4.4 Current and Charge

The categorization distributions are significantly different according to a chi-square test ( $p < 0,1\%$ ). The difference consists in a conversion of the "substance" and "property" categorizations.

## 5. Discussion

### 5.1 Some Observation from the Data

(i) In these samples the high percentage of current as substance is noteworthy: Grade 10 students categorize current even more often than grade 8 students as a substance. It may be interesting to compare these results with a combined questionnaire asking for "the best analogy" for current (see Appendix part C). Three items were offered naming substances (e.g. "liquid"), and some items which name occurrences ("rain", "stream of air", "river", "stream of sand"). There is a significant difference in the spectrum of answers. But globally, 81% of the 10 graders, and 90% of the 8 graders opted for an occurrence as best analogy. Both samples had a peak with "river" (38% vs 60%). Thus the conclusion may be plausible that 10 graders think of current in terms of "moving electrons", but the predominant aspect is not the movement, but the substantial things that move (can be at rest, can be stored, etc.). Thus "current" is an ambivalent term.

This ambivalence is very similar to that of the common sense word "electricity" which exhibits a similar spectrum.

(ii) It is of some interest that current is different from energy. The didactic relevance of this fact is obvious. Of similar relevance is the fact that voltage has no significantly different category distribution from energy. (But 8 graders have a significant difference.)

### 5.2 Uses and Abuses: A Cautionary Note

The C-questioning technique presented so far can easily be made to be a paradigm for the abuse of statistics. From interview data and from written arguments (especially in Maichle's investigation) we know that students have very different reasons for their choices.

(i) Analysis of data gathered by Maichle<sup>3</sup> from University students (future teachers) reveals that even in this sample a few adults shifted from "is a property" to "has a property". Similar shifts have been observed from "substance" to "event". E.g., a girl from Maichle's sample subsumed "bulb" under the events, because "a bulb is shining". And shining, she rightly felt, has to be categorized as a process.

Another informative example is the categorization of current as a process, because "a process is needed to generate current". More examples could be quoted. But these few may suffice to highlight the interpretation problem. Maichle remarked that there is no objection to categorization procedures of students which are against logical norms. This is true, provided we know the categorization strategies. If we know them, we gain a lot of information about the way students' minds work, and this may be of considerable value to teachers. Thus I think trials have shown so far that the instrument is advantageous if used as an interview guide, or at least if combined with written reasonings. It then reveals predominant subsumers, subsuming strategies included. Otherwise it is only a very rough information about representations which has to be interpreted with great care.

The technique can be useful also as a didactic device by instigating discussions in different phases of the developing knowledge of students.

(ii) Stimulated recall interviews with rather young students (grade 6) show that very often categorization is done "intuitively", i.e. no reason can be verbalized. Of course, this does not mean that the process is purely random. It means, that C-questioning is an associative technique.<sup>4</sup> It may have some didactic value even in this case if it is used as an incentive for group discussions.

### Notes

- 1 This categorization has been adopted from A.N.Whitehead, Adventures of Ideas. Macmillian, New York 1933, p.49. See also chpt.4 of W.Jung, Aufsätze zur Didaktik der Physik und Wissenschaftstheorie, Diesterweg, Frankfurt/M., 1979.
- 2 It may be interesting to note that the grade 8 sample exhibits the same differences, with lower significances ( $p < 5\%$ ), also in the case of voltage and energy.
- 3 A complete analysis of Maichle's data will probably be available in 1985. Some of her results have been presented in the following paper: U. Maichle, Representation of Knowledge in Basic Electricity and its Use for Problem Solving. Proceedings of the International Workshop on Problems Concerning Students' Representation of Physics and Chemistry Knowledge, Sept. 1981, Ludwigsburg, 174-193.
- 4 See W.Jung, Assoziationstests und verwandte Verfahren. In: R.Duit, W.Jung, H.Pfundt, Editors, Alltagsvorstellungen und naturwissenschaftlicher Unterricht. Aulis Verlag, Köln, 1981, 196-222.  
There is no reason to suppose that answering the questionnaires was not felt to be a serious affair. "Sharp" distributions like those of "electron", and of common sense words like "run" (see Appendix) give evidence of the fact that students made "rational" choices.

### Appendix

(Translation of the original C-Questionnaire)

Name:

Class:

#### A) Arranging into Lists.

Here are some physics concepts, and you are asked to add them into one of the following lists.

- List 1 contains occurrences: A violent storm, chewing of bread, a box fight, car driving, ...
- List 2 contains objects (substances): A chair, a car, an airplane, a molecule, a bottle of juice, a book, ...
- List 3 contains properties: Bravery, brave, firmness, firm, hard, dark, thick, thin, transparent, conductive, ...

Now write into the box belonging to each of the following words the number of the list (1,2,3), into which the word belongs. Do you find no such list, write some other words beside the respective word, which all could belong to a new list.

Concepts you know from physics instruction are to be understood according to their use in physics!

|                           |  |  |
|---------------------------|--|--|
| electric current.....     |  |  |
| a run before leaping..... |  |  |
| electricity.....          |  |  |
| sleep.....                |  |  |
| energy.....               |  |  |
| verve.....                |  |  |
| jolt.....                 |  |  |
| force.....                |  |  |
| work.....                 |  |  |
| voltage.....              |  |  |
| charge.....               |  |  |
| electron.....             |  |  |

Now look again at these words and write down those which in everyday life have a different meaning from their physics meaning: .....

(Part B is omitted. It concerns mechanics only.)

C) Comparing

With what can you compare current? Mark the best comparison (analogy) by a cross:

|                     |  |  |
|---------------------|--|--|
| powder.....         |  |  |
| pulp.....           |  |  |
| liquid.....         |  |  |
| rain.....           |  |  |
| stream of air.....  |  |  |
| river.....          |  |  |
| stream of sand..... |  |  |

THE MEANING OF CURRENT AND VOLTAGE IN EVERYDAY LANGUAGE AND ITS CONSEQUENCES FOR UNDERSTANDING THE PHYSICAL CONCEPTS OF THE ELECTRIC CIRCUIT

Reinders Duit

1. Overview of learning difficulties induced by everyday language

Many learning difficulties in physics instruction are - at least partly - induced by the everyday language (see e.g. Pfundt, 1981; Logan, 1981). These difficulties are not surprising if linguistic research on relations between language, world views and thought is taken into account. Although strict linguistic relativism as represented by Whorf seems now to be outdated, linguists representing different points of view appear to agree that the language we speak has considerable influence on our world views and on the way we think (see Gipper, 1972).

There seem to be three main sources of language-induced learning difficulties.

(a) Language provides notions

Many notions of natural phenomena and processes are imbedded in everyday language. Quite a lot of them have been revised by science, some even centuries ago. The sentence "the sun rises", for instance, does not take into consideration that Copernicus, Kepler, Galilei and others provided us with the helio-centric point of view.

Linguistic investigations and research of students' alternative frameworks have revealed many other examples, especially in the areas of mechanics, astronomy, heat and optics. As far as the area of electricity is concerned, no such ancient notions seem to be conserved in everyday language. Electricity is not among the phenomena which effect our senses directly. Our knowledge of electricity is comparably young. The learning of electricity will therefore not be hampered by "Aristotelian" notions, as is the case for mechanics and optics. Today's everyday language does of course contain notions on electricity,

namely in the way we speak about electricity and electric devices in daily life.

(b) The structure of language leads and misleads thinking  
The second source of learning difficulties originates from the logical structure provided by language. There is a correlation between the structure of language and logical thinking. Linguists are of the opinion, for instance, that the Aristotelian system of basic categories and principles of logical reasoning was deduced by Aristotle from the ancient Greek language. The grammatical structures of this language and of the Indo-European languages are very similar. Therefore, native speakers of the latter languages implicitly learn Aristotelian logic when learning these languages (see e.g. Hayakawa, n.d.). The basic categories and the principles of logical reasoning are valid both in daily life and in physics contexts. But some usages of the provided logical system in daily life are misleading in a physics context. In a daily life context the word force, for instance, is usually categorised as a quality or even a property of an actor. We say, for instance, that a weightlifter has force (see Duit, 1984). The physical concept of force is conceptualised as a relation between objects (i.e. as a measure of the strength of interaction). There are other examples of employing the "quality of an object" category in a daily life context where physics uses the relation category (see Jung, 1979). Voltage, to take an example from electricity, is conceptualised in daily life and even in some introductory physics courses simply as a quality of electric sources (e.g. batteries or the electric grid). In physics voltage should be categorised as relation between qualities at different points of the electric circuit.

The main features of Indo-European languages include the subject-predicate-object-structure of sentences and the verb "to be" which allows existence to be conferred to objects and events. These features have important consequences. They seem to be responsible for the tendency in these languages to

substantivate, i.e. to think within the thing category and they seem to support a thinking in sequences of single cause-event-elements (see Gipper, 1956; Wein, 1965, Hayakawa, n.d.). Bridgeman (1943), for instance, is of the opinion that the mentioned tendency to substantivate is responsible for a common tendency to think of energy in terms of a quasi-material substance and not in terms of an abstract balancing quantity.

The above-mentioned tendency to think in sequences of single cause-event-elements has important impact on learning electricity. We know from several studies (see Härtel, 1982; Closset, and Shipston in these proceedings) that students concentrate on local processes and prefer sequential reasoning when dealing with problems of the electric circuit. They seem to have severe difficulties in taking all parts of the circuit into consideration, they seem to be almost unable to think of the circuit in terms of a system. Of course, these difficulties are not restricted to the electric circuit. The inability to think in interactions rather than in single cause-event-elements hampers human understanding in many complex fields.

(c) Concept names are also used in everyday language  
There is a third source of language induced learning difficulties. The concept names used in physics are very often borrowed from everyday language. Quite frequently, this is motivated by the intention to point out some basic features of the concept via the concept name already. Whether this is really true for some concepts of elementary particle physics (such as charm and strangeness) will not be discussed here. Undoubtedly it is true for the concept of current in German. We call the corresponding physical concept "Strom" (the literal translation would be "stream"). The motivation originates in fluid models of electricity which were developed during the 18<sup>th</sup> century. Very often the words borrowed from everyday language do not lead to main aspects of the physical concept. They are, on the contrary, misleading. This is true, for instance, for the

concept of current. The following sections will deal with the everyday meanings of this concept and the concept of voltage in more detail.

## 2. Some remarks on the range of the following considerations and on association tests

The meanings of names for the same physical concept in different languages, usually differ from each other. The meaning of the word "Strom", for instance, in German differs from the meaning of the word "current" (which stands for the same concept) in English. Therefore, considerations on learning difficulties induced by the everyday meaning of a concept name are valid only within the context of the specific language...

Empirical evidence on the meaning of the words "Strom" and "Spannung" in everyday German, which I shall present in the

It is surprising that this meaning is to be found very seldom among associations grade 6 students before physics instruction (about 12 years old) give to "Strom".

Only about 1% of all these associations can be categorised as "something flowing". It predominates an "energetic" meaning of "Strom", namely "Strom" and "Energie" (i.e. energy) are closely connected. 35% of the students wrote down the word "Energie" when asked for associations with "Strom" (see fig.1),

|                                                    |     |                             |     |
|----------------------------------------------------|-----|-----------------------------|-----|
| Licht (light)                                      | 44% | Strom                       | 44% |
| Steckdose (electric outlet)                        | 43% | Öl (oil)                    | 18% |
| Energie (energy)                                   | 35% | Energiesparen (save energy) | 14% |
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Fig. 1: The most frequent

Fig. 2: The most frequent associations with ENERGIE

namely in the way we speak about electricity and electric devices in daily life.

## (b) The structure of language leads and misleads thinking

The second source of learning difficulties originates from the logical structure provided by language. There is a correlation between the structure of language and logical thinking. Linguists are of the opinion, for instance, that the Aristotelian system of basic categories and principles of logical reasoning was deduced by Aristotle from the ancient Greek language. The grammatical structures of this language and of the Indo-European languages are very similar. Therefore, native speakers of the latter languages implicitly learn Aristotelian logic when learning these languages (see e.g. Hayakawa, n.d.). The basic categories and the principles of logical reasoning are valid both in daily life and in physics contexts. But some usages of the provided logical system in daily life are misleading in a physics context. In a daily life context the word force, for instance, is usually categorised as a quality...

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| liquid.....         |  |  |
| rain.....           |  |  |
| stream of air.....  |  |  |
| river.....          |  |  |
| stream of sand..... |  |  |

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## 2. Some remarks on the range of the following considerations and on association tests

The meanings of names for the same physical concept in different languages, usually differ from each other. The meaning of the word "Strom", for instance, in German differs from the meaning of the word "current" (which stands for the same concept) in English. Therefore, considerations on learning difficulties induced by the everyday meaning of a concept name are valid only within the context of the specific language...

Empirical evidence on the meaning of the words "Strom" and "Spannung" in everyday German, which I shall present in the following sections, is mainly based on association tests. Students are presented concept names on a screen, each for 30 seconds. They are asked to write down what comes to mind when they are confronted with the words. This method has both advantages and pitfalls which I have discussed in another paper (Duit, 1983). Here I wish to point out only some main aspects. Associations provide researchers (and teachers) with a preliminary insight into ideas which come spontaneously to the minds of the students when confronted with a word. They do not enlighten the denotative meaning of a word (i.e. the way a concept may be defined) but throw some light on the connotative meaning (i.e. on the associative framework of a concept).

## 3. Meanings of the word "Strom"

The etymological origin of the German word "Strom" had the meaning of something flowing. This meaning is still in use. We use the word "Strom" for a large river (e.g. the Rhine) but also for something flowing in general. We speak, for instance, of "Flüssigkeitsstrom" (i.e. a flowing fluid) or of "Menschenstrom" (i.e. a crowd moving in one direction).

It is surprising that this meaning is to be found very seldom among associations grade 6 students before physics instruction (about 12 years old) give to "Strom".

Only about 1% of all these associations can be categorised as "something flowing". It predominates an "energetic" meaning of "Strom", namely "Strom" and "Energie" (i.e. energy) are closely connected. 35% of the students wrote down the word "Energie" when asked for associations with "Strom" (see fig.1),

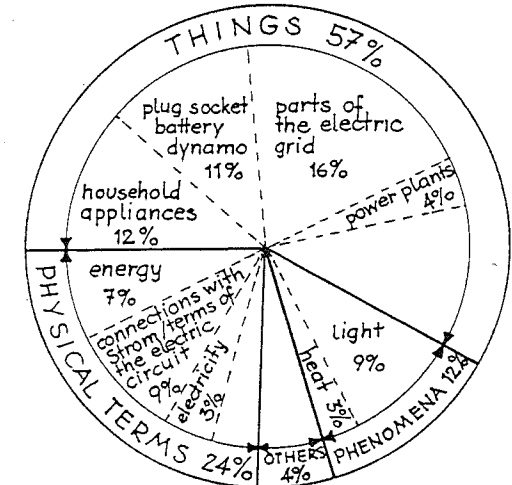
|                                                    |     |                             |     |
|----------------------------------------------------|-----|-----------------------------|-----|
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| Steckdose (electric outlet)                        | 43% | Öl (oil)                    | 18% |
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Fig. 1: The most frequent associations with STROM

Fig. 2: The most frequent associations with ENERGIE

Figures give fraction of students associating the listed words. English translation of the German words in brackets.

Fig. 3: Associations with "Strom". The same students as in fig. 1 and fig. 2. The percentages are based at all associations given by the 147 students here.



while 44% of the students gave the word "Strom" as an association with "Energie" (see fig. 2). Other associations given to "Strom" support the "energetic" meaning of this word (see fig. 1 and fig. 3). This is true, for instance, for household appliances which need electricity. The associations given by the grade 6 students reflect the use of the word "Strom" in daily life. "Strom" is quite frequently used in the meaning of energy. "Strom" is very often seen as an energy form. We say, for instance, that it is necessary "to save" Strom (Strom sparen).

Energy supply industries try to convince us that "Strom" is the energy we need most urgently.

There are results in other empirical studies which support my findings (see e.g. findings of v. Rhöneck's research presented in these proceedings). Maichle (1982) has found that many students use a "give-schema" in considerations on current flow in the electric circuit: the battery gives something (mostly current) to the bulb. This schema may also be seen within the energetic notion of "Strom".

It is interesting that in Swedish the situation concerning the concept name for current is very much the same as in German (see Andersson, 1980). Whether this is also true for the English language I do not know exactly. The etymological origin of "current" has approximately the same meaning as "Strom", namely "running" and "flowing". This meaning is still apparent in modern English. Current also seems to have an energetic meaning in English. Gilbert and Osborne (1979) have found a "container theory" among many students, who thought that current may be stored or be contained in some way in a battery. But the energetic aspect of current is not as strong as in German. Current is not seen as an energy form. It is, for instance, not possible to admonish someone to "save current".

For the context of German it is justifiable to draw the following conclusion. The word "Strom" does not indicate main aspects of the physical concept of current for students at the

beginning of physics instruction. On the contrary, the word is misleading on the path to the physical concept. There will be the following misunderstanding in physics lesson. The teacher says "Strom" and means "flowing charge". The students hear "Strom" and think of that what is transported while the teacher's Strom is flowing, namely of an energy-like entity. It is somewhat unfortunate that this misunderstanding stays hidden for a long time because many processes discussed in instruction can be interpreted in both models, namely in the teacher's charge-flow-model and in the students' energy-flow-model. The misunderstandings become obvious only, when the above-mentioned models lead to different predictions. This is true, for instance, for the notion of "Stromverbrauch" (i.e. consumption of current) which is very common among German students. This notion makes sense only within the energy flow model in the following way. The energy like-entity Strom is consumed in the bulb, i.e. it is used up while changed into light and heat.

#### 4. Meanings of the word "Spannung"

The German name for the concept of voltage, namely Spannung, is also borrowed from everyday language. It has the meaning of mechanical stretch, tension or stress on the one hand and of excitement, expectation and anxiety on the other. When the context of electricity is concerned, the word "Spannung" is used much less frequently than the word "Strom". It characterises qualities of electric sources (like batteries and the electric grid; compare section 1) and of Strom (i.e. electric current). These qualities may be outlined quite well by the word force. Very often "Spannung" indicates mainly "high voltage".

The associations with "Spannung" given by my grade 6 students reflect these uses of the word Spannung (see fig. 4).

I think that these meanings are not as misleading as the everyday meanings of Strom. The notion of a stress may well be employed to underline main features of the concept of voltage. But one has to be very careful that "Spannung" is

|                             |     |
|-----------------------------|-----|
| Krimi (crime)               | 25% |
| Strom                       | 22% |
| Aufregung (excitement)      | 15% |
| Gummi (rubber)              | 13% |
| Hochspannung (high voltage) | 10% |

Fig. 4: The most frequent associations with Spannung 147 students, grade 6, compare fig. 1 - 3.

not simply categorised as quality of electric sources or of current. This restriction would hamper an understanding of "Spannung" within the category of relation which provides the genuine physical conceptualisation of voltage.

A brief remark on the English concept name may conclude this section. The word voltage has not been borrowed from everyday language. Nevertheless, physics instruction should take into consideration how this word is used in daily life, e.g. in conversations about electricity.

### 5. Summary

This paper set out to demonstrate that everyday language influences the learning of electricity. There are two aspects which seem to be of great importance. On the one hand the logical structure of language leads to a way of thinking which is not appropriate in electricity. This appears to be true especially for the inability of most students to think of the electric circuit in terms of a system. On the other hand the everyday meanings of concept names may hamper an understanding of the physical meaning. This appears to be true especially for the concept name "Strom" in German. The everyday meanings of this name lead to an energetic point of view and not to the flow model of electricity. Therefore, both points of view have to be very carefully discussed in physics instruction. Students have to become aware that the same word is used very differently in daily life and in physics.

This paper dealt with learning difficulties induced by everyday language. It is most important to bear in mind that the language teachers use in physics instruction is responsible for some further problems. The word "Strom", for instance, is not used consistently in the physical meaning in German textbooks and by

German teachers. Another example is given by Shipstone (1984). He is of the opinion that the above-mentioned sequential reasoning of students with regard to current flow is supported by teachers and textbooks. Very often they explain the flow of current in approximately the following way: "Current is flowing through the first connection wire, through the switch, then to the bulb, through the bulb, then back to the battery".

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# THE DEVELOPMENT OF CONCEPTS BY MEANS OF DIALOGUES CENTRED ON EXPERIMENTS

Christina Kärrqvist

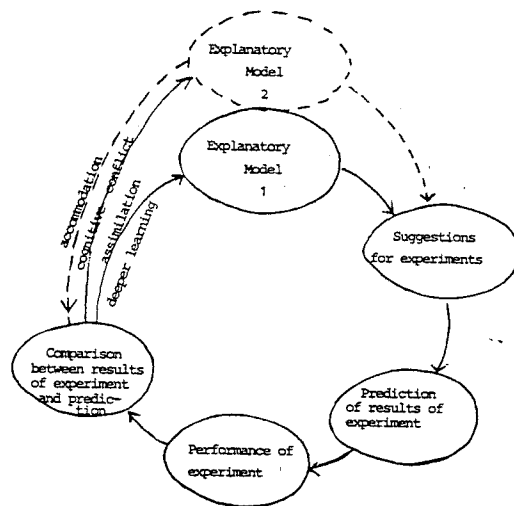
A study of the development of concepts in four 13-15-year-olds in videorecorded learning situations has been conducted with the following starting-points:

1. A constructivist view of knowledge and of the pupil. The pupil is active, creative and constructs his own knowledge. The pupil has conceptions which he/she uses to understand the world around him.
2. Learning is seen as a transition from one way of perceiving a phenomenon to a new way of looking at the same phenomenon that differs qualitatively from the previous one.
3. By deep learning is here meant a process of integration in which a new way of looking, a new model or a new concept is related to other concepts and to earlier experience. The more the pupil varies his experiments, the greater the number of relationships that are created and the greater the degree of integration. This leads to deeper learning.

Our study deals with learning in relation to the functioning of a DC circuit. A model for learning is presented in which the concepts assimilation, accommodation and cognitive conflict are necessary, but also hard-core conception, protective belt, auxiliary hypotheses and explanatory areas or systems.

Six qualitatively different models of explanation are described. Examples are given of the explanatory models used by a pupil when working with various experiments. Depending on the conception the pupil has, it is possible to give a list of examples of tasks that probably challenge the pupil and another of those that do not. A summary is provided of the challenges that have been found.

### The model for learning/learning model



The learning model implies that an individual has a more or less clear, perhaps intuitive, idea of how an electric circuit works. This may mean that the only requirement is a wire to connect the source of current to the bulb. It is then called a unipolar explanatory model 1. Take a desk lamp, for example, plug it into the wall socket and it will work. Doing this experiment shows that this model is valid. The result is understood and the experience is assimilated to model 1. The greater the number of experiments carried out in which the results are the ones expected, the more firmly model 1 is established.

Model 1 is only challenged when the individual suggests an experiment, or an experiment is suggested to him/her, the results of which are contrary to the ones predicted. The individual experiences a cognitive conflict: "No, that's not what I expected. Now I don't understand a thing." In this situation, a pupil needs to be creative and to construct an alternative model of explanation and is probably motivated

to listen to alternative suggestions. If the pupil succeeds in finding a new model or in modifying an old one so that the experiment is understood, i.e. that the model can be used to explain the previously inexplicable experiment, and if the pupil can also use the new model of explanation to successfully predict the results of new experiments, the pupil probably accommodates, i.e. changes models.

We have found evidence of the following six models of explanation among the pupils:

- |                                                                                                                                                                                 |                                                                                                           |                                                                                                               |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| 6. The current intensity depends on the appearance of the circuit, is conserved in the circuit. Current begins to flow simultaneously all over the circuit when this is closed. | <u>Ohm's model</u><br>Current $\neq$ Energy                                                               | Energy is transmitted with the aid of electric current in amounts depending on the appearance of the circuit. |
| 5. The battery always gives the same amount of current. Current circulates and is conserved in the wires, not in the bulbs. Current is divided equally in the branch wires.     | <u>Constant Current Source Model</u>                                                                      | Equal amount of energy is transmitted per unit of time.                                                       |
| 4. Current is used up as it passes the components in the circuit.                                                                                                               | <u>Current Consumption Model</u><br>Current is transformed into energy.                                   | Energy is transmitted linearly.                                                                               |
| 3. Current circulates in a closed circuit.                                                                                                                                      | <u>Closed Circuit Model</u><br>Current is transformed into energy or When current passes energy is formed |                                                                                                               |
| 2. The battery supplies opposite plus and minus currents.                                                                                                                       | <u>Two-component model</u><br>Plus and minus currents meet and form energy.                               | Energy is formed.                                                                                             |

1. The battery gives current to the bulb.

Unipolar model  
Current  $\approx$   
Energy

Energy is  
transmitted  
linearly.

- | Current                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Model | Energy |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|--------|
| 1. Energy is transmitted with a single connection from energy source to energy receiver. For the pupil, current and energy mean roughly the same thing. Energy in the form of current is stored in the battery and is transmitted by a wire to a bulb, for example, where it is consumed and transformed into light and heat. In this causal model, the battery is considered as an agent, the bulb as a receiver, the current or energy as the object and the electric wire as an instrument. We call this model <u>unipolar</u> . Compare modèle unipolaire (Tiberghien, 1974) and GIVE-schema (Maichle, 1981).                                                                                                                                                                                                                                                                                    |       |        |
| 2. The energy source has a bipolar connection and gives both positive and negative charges or currents. These meet in the energy receiver, which can have an unipolar or bipolar connection. The receiver has to have both kinds of current to be able to work. Energy is then produced in the form of heat and light. The model is called <u>two-component</u> by us. Compare "courrants antagonistes" (Tiberghien, 1974), clashing currents (Osborne, 1981) and Model 1 (Shipstone, 1984).                                                                                                                                                                                                                                                                                                                                                                                                         |       |        |
| 3. The energy source and receiver, in fact all components are connected by two poles in a circuit. Current circulates in one direction in the closed circuit. The closed nature of the circuit is the necessary and adequate condition for the circuit to function. When current flows round and rubs against the material in narrow passages energy is formed. The circuit is only viewed in a qualitative way. To find a closed circuit and to be able to follow the path of the current round this is a sufficient explanation of how an electric circuit works. Although the concept of energy is firmly associated with the transmission from source to receiver, and the concept of current is strongly linked to circulation, the pupil does not hesitate to say that energy circulates in the circuit. The wedge driven in between the concepts of current and energy by the idea of current |       |        |

circulating round a closed circuit does not create a cognitive conflict in the pupil. He/she is content with this closed circuit model. To find the closed circuit is the concrete and sufficient thing for the pupil. He/she is not concerned with any further explanation of how the circuit functions. The model is on a technical level.

4. The circuit is regarded not as a system that is independent of time, but rather in time-dependent sequences. Current is consumed by the resistances of the circuit as it passes through them. A small amount of current returns to the battery, however. This is an atomistic way of looking at the parts of the circuit, piece by piece, step by step. The pupil attempts to assimilate the assumption that current circulates in the circuit to the conception of a linear transmission of energy. This results in this current consumption model. Compare the time-dependent model, (Riley, 1981) and the sequence model (Shipstone, 1984).

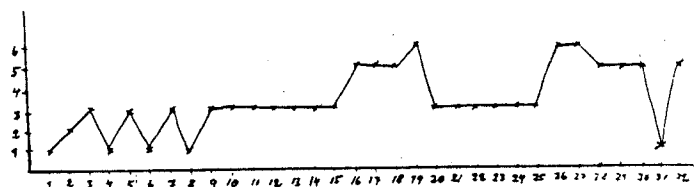
5. Circuit elements with bipolar connections, circulation of current and a closed system are self-evident. The battery is assumed to be a constant source of current, which sends out the same amount of current regardless of the appearance of the circuit. Only as time goes on does the battery become weaker and gives less and less. The circuit is regarded partly in a holistic way, as a system in which the idea of sharing is a strong element. Two bulbs have to share what one bulb would otherwise get. That is why the pupil supposes that both two bulbs connected in series and two bulbs connected in parallel shine more feebly than a single bulb. But the circuit is also viewed in an atomistic way, in which the current first flows through one component, then the next, in chronological sequences. The current is shared out equally in branch wires irrespective of their appearance, because this is the fairest way. The current is not consumed. It is of the same magnitude all over the circuit, but not in the bulbs.

We call this model the constant current source model (compare Cohen, 1982).

6. The energy source initiates a circulating current in the closed metal circuit simultaneously at all points. The intensity of the current is conserved. The transmission of energy takes place with the help of electric current in the wires. The circuit is treated as a system in which a change in a subsystem at once changes the conditions in the whole system. The current is proportional to the voltage and inversely proportional to the resistance, in accordance with Ohm's Law. The energy transmitted per unit of time is proportional to the resistance, but also, simultaneously, to the square of the current. This is called Ohm's model.

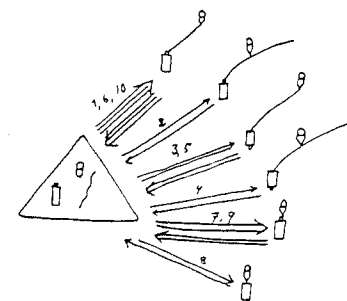
The model of explanation that a 15-year-old pupil shows signs of using is plotted in the following diagram. The pupil has worked with various experiments for a total of about 8 hours. On the horizontal axis the experimental situations are indicated. On the vertical axis the six models of explanation are set out.

Current  $\neq$  Energy



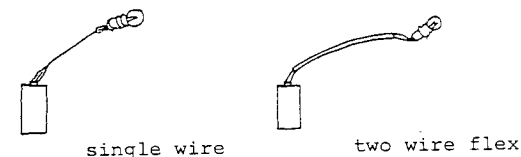
Current  $\neq$  Energy

The pupils starts with a concept of current that lies very close to that of energy. When given a 1.5 volt battery, a bulb and a piece of wire he connects them as in the figure below. The numbers indicate the chronological order in which the pupil connected the components (exp. 1).

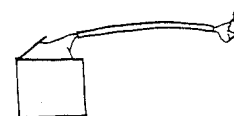


He uses a unipolar model. When later talking to me, the pupil, P, constructs a bipolar model of explanation. Let us look at the experimental contexts in which P returns to his unipolar model.

Experiment no. 4 is started by P. He asks himself how a desk lamp is connected and asks for a flex containing several wires. He obtains both in insulated single wire and a two-wire flex and attempts to connect the components as follows:



The context is altered when P is given a 4.5 volt battery. In this context, he uses a bipolar connection immediately. (Exp. 5)



P: "Though it goes in the same way in a circle, though it now goes closer, like"

The pupil wonders how 1.5 volt batteries work and manages to connect one with two poles. A week later he tries again, but then returns to the unipolar connection. (Exp 6)

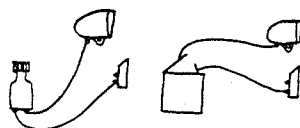
In Experiment no. 8, P is allowed to investigate a gas-lighter and draws what he imagines to be its cross-section, showing a unipolar model:



When you press the button, contact is made and something begins to glow, he says.

In a dialogue the pupil develops his model of a gas-lighter into explanatory model 3 and goes on to construct imagined cross-sections of many different electrical systems, such as an iron, toaster, a lamp-holder and an electric heating pad (experiments 9-15). For months the pupil works with a consistent bipolar model, common to the explanatory models 3, 5 and 6 which he seems to have completely accommodated to.

A challenging context (no. 31) makes him go back to using the unipolar model again. This happens when he has to connect two bicycle lamps, one to a generator and one to a battery.



The unipolar model of explanation is strongly dependent on the context. This is why a richly varied experimental context, and preferably ones that are particularly challenging, may conceivably develop the pupils' knowledge in the area.

P is often content with explanatory model 3. He draws a cross-section of an iron as a single coil.



The coil "goes all over it, so it gets hot all over, like"  
The pupil has drawn a closed circuit and indicates a circulating current. This is how the iron works.

The pupil uses a sharing model if the context invites it. In experiment no. 16, the pupil explains why two bulbs connected

in series shine less brightly than one. He says that "when there's only one, it gets all the current. When there are two, then they have to share the same current". In experiment no. 19 he explains why a bulb shines just as much no matter whether one or two batteries are connected to it (in parallel). "The batteries last longer as it takes half from each". In experiment no. 26 he says, when comparing the same thing "The batteries only go at half. They keep longer". When comparing circuits with two bulbs connected in parallel and those with one bulb, the pupil says. "The lamps shine normally, but the current is used up twice as fast". (Exp. 27)

The idea of sharing is common to these four situations. In the explanation of experiment no. 16 lies an assumption that the battery gives the same current, irrespective of the appearance of the circuit. This is a sign that P is using explanatory model 5. In the other examples, the time argument implies that the battery is regarded as a variable source of current. As P has always denied the consumption of current, and consequently has never used explanatory model 4, we indicate experiments 19, 26 and 27 as examples of explanatory model 6.

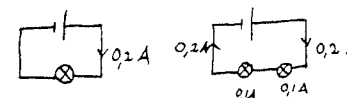
P develops explanatory model 5 again and again. He explains a short circuit in the following way, for example:

P: "Instead of the current going in here, in the bulbs, it goes round out here" in the short-circuiting wire "and then it goes round like this. It doesn't go through the bulb".



At the bottom of this lies the assumption that the battery is a constant current source. P interprets the phenomenon short circuit with his own structure in an assimilating activity.

In experiment no. 18 P compares two circuits and predicts the amperage.





P: "But I don't really know what it's like in the bulbs".  
He then discusses the series circuit:

P: "But now it doesn't shine so brightly, so now it ought to be ---- Did the lamps shine with 0.1?"

The teacher answers "yes".

P: "That's strange because the current goes like this (0.2 from the battery) and then like this, they don't come at the same time (through the bulb). The current doesn't need to divide, but they only shine half as brightly all the same ...

There's resistance here (in the bulbs), so then there is, then it goes slower like and then it's only 0.1 ... and then when it comes out on where it's easy, then it's 0.2 again. But then in this bulb it gets narrower. It gets hard. It becomes 0.1."

The teacher says that it is strange that 0.1 A can just disappear and ask where it goes to.

P: "I thought that if it sort of slowed down and gets narrower here, as it does in the tubes here (draws diagram). Here they all come, several of them pass here and they have to pass two at a time, or in some way."



The pupil constructs an explanation of how amperage can be thought of as decreasing in the bulbs. This explanation may be regarded as an auxiliary hypothesis to save the hard core conception, no. 5, the main assumption of which is that the battery is a constant current source.

The study has provided information about the experimental contexts that have, and have not, challenged the pupils' conceptions and they are listed below for one of the models.

# CURRENT CONSUMPTION MODEL

## Challenge of 4

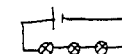
## Non-challenge of 4

Ex. 1 Compare how the bulbs shine

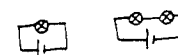


with short and with long wires

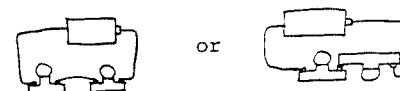
Ex. 2 Measure the current at different places in the circuit



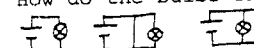
Ex. 3 Compare the current in the circuits



Ex. 4 In which circuit do the bulbs shine most?



Ex. 5 How do the bulbs shine?



The results also support our constructivist effort. During a session of 60 minutes the pupils proposed several suggestions and ideas, sometimes one every other minute. If the pupil gets the chance and knows what is expected from him, he is very active, formulates and tries to solve his own problems in a never ending process.

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### HOW DO 12-YEARS-OLDS APPROACH SIMPLE ELECTRIC CIRCUITS?

A Microstudy of Learning Processes.

Ruth Prüm

Our aim was to investigate the development of ideas children  
hold about simple electric circuits among a small group of stu-  
dents in the course of instruction.

The teaching style was kind of an experimental one each-  
centered phases alternate systematically with pupils-centered  
ones, pupils were explicitly encouraged and given time and ma-  
terials to make their own experiences so that they were free to  
follow their own plans. There were three lessons a week under  
normal school conditions. The unit went on over a period of 6  
weeks.

We focussed our investigation on four boys sitting together at  
one table and usually working in two groups. During all the  
lessons their activities were recorded on videotape. In order  
to get informations about class-atmosphere, feelings and in-  
volvement of the students transcriptions were not restricted to  
physics topics, but were done of the complete tapes.  
Our interpretation is based on the psychological theory of hu-  
man action developed by v. Cranach and on the theory of think-  
ing and acting advocated by Aebli.

V. Cranach says that human action is goal-directed and that an  
acting person always has a plan how to achieve its goal. As  
actions take place in a social context, a person is able to  
grasp an understanding of the goals of an other person on the  
basis of social conventions - v. Cranach gave prove to this  
thesis in several investigations.

Aebli postulates that thinking is not completely different from  
action and that both forms are serving the same purpose: to  
construct relationship between elements. Thinking means ar-  
ranging one's doing. When interpreting students' actions, we  
first tried to find out their goals. Here videotapes prove to  
be a helpful tool because they permit to see an action again and  
again. From the relations which students express in their words

and in their actions and from the adequacy or inadequacy of their plans, we conclude their conceptions.

I'll now be talking about the activities of a single boy, in the following called S, in a certain lesson when he for the first time had the chance of handling these materials: a board with more than seventy pins that serve as contacts, 5 bulbs, wires and two hairclips that serve as switches.

In the preceding lessons the pupils worked upon the questions of:

- how to light a bulb with a flat battery
- bipolarity of electric elements such as monocells, dynamos, bulbs in a holder, electromotors, and electric bells
- short circuits (here they had an indicator that told them whether there was a short circuit or not)
- electric conductors and isolators,

and they did a written test on these topics. So far pupils had only used one source and one resistor in a circuit.

Before handing the material over to the children, their teacher told them that they were not expected to fulfill a special task but were free to construct circuits as they liked. One girl mentioned the idea to colour the bulbs, and was allowed to do so.

S immediately begins to connect wires and bulbs to form a closed circle (fig. 1a)) without first clearing the board. He seems satisfied and says to himself, that he has now already constructed something that makes sense. He takes the battery, touches one contact-pin with one terminal - the other terminal is fixed to the short circuit-indicator - and verbally encourages the bulbs to glow (fig. 1b)). Then he puts the battery aside and colours the bulbs.

After finishing that he controls the connections and thinks loudly: "This is now connected, it's an electric circuit. Now it has to be connected with both ends". He detaches the indicator from the battery and tries to hold both terminals against the contact-pin (fig. 1c)). Again he tells his product to glow,

and finally puts the battery aside. He asks the teacher, who

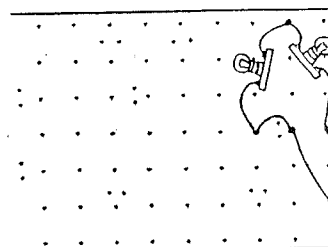


fig. 1a

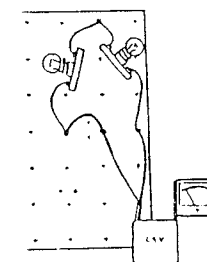


fig. 1b

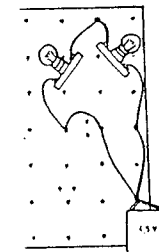


fig. 1c

happens to pass by, what to do. But she doesn't find S's construction among the other materials and tells him, first to remove all things from the board and to put the battery into a proper place and then to start again. S agrees to remove the materials.

When doing so, he notices that one bulb wasn't fixed correctly to the holder, and takes this as the mistake. He starts as before and connects wires and bulbs to form a circle (fig. 2a)). In this process he is threetimes engaged in verbal discussions with the boy sitting opposite to him (O), and twotimes his neighbour (J) asks him for cooperation. S keeps on constructing. He promises cooperation for the time after completing his present task. He seems to be rather confident.

After closing the circle (fig. 2a)) he sees the need for a battery when the fourth boy at the table (Ls) asks where to place his own one. Without hesitation S takes the battery, opens the circle and connects it correctly (fig. 2b)). While doing so he invites his neighbour to watch the bulbs glowing in a few moments, and he realizes that he and his neighbour are forced to cooperate because there is only one battery. But there is another failure - later it turns out that the battery had run out of power. S is perplexed. He asks the others for confirmation that his circuit normally would have to work, but there is no reaction.

He examines his circuit then begins to replace two of the bulbs by wires (fig. 2c)), and tells himself to pay attention to the fact that "bulbs don't pass through". This makes him feel discontent.

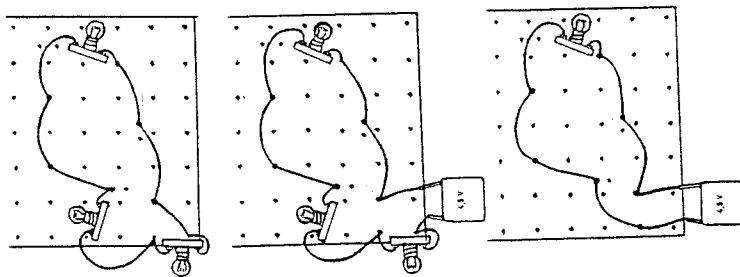


fig. 2a

fig. 2b

fig. 2c

But the new circuit (fig. 2c)) doesn't work either. S is convinced that it would have to, and finally he tries to get help from the teacher - but she is engaged at the moment. S does another test on bulbs connection to the socket and waits for the teacher. Suddenly he realizes that the group opposite to him (O, Ls) are constructing a circuit with more than one bulb in series, and he calls their attention to this supposed mistake. O disagrees and argues that all things are conductors. S stresses that bulbs will not "let pass through". Here the discussion ends, S concentrates on his own circuit, the other boys continue theirs.

But there was another disturbance for S-J wants the battery now and takes it off. S protests, but not very decidedly, he has the idea to try changing the bulbs first. At the same time the circuit of the neighbourgroup works, they triumph.

S has not the chance to get the battery back for testing whether the bulb caused the failure. He gives up his first goal and now wants to build a big series circuit in cooperation with his neighbour. But J first completes his present circuit. Thereby it turns out that the battery has run out of power.

Now I want to give some interpretations.

First the observer is surprised that S doesn't begin at one terminal of the battery but with a bulb in the middle of the board - i.e., his teacher later tells S to choose a different way of proceeding. But this becomes less surprising, if one supposes that S wants to build an object, kind of an electric apparatus. In this case the battery is not part of the object, comparatively a wall-plug is not part of a hair-dryer. If you imagine someone wants to construct an electromotor you would not expect him to start from the battery.

The assumption that S, and I suppose J too, don't regard the battery as a part of their circuits makes explicable why:

- S and J don't cooperate although they did agree to form a group. There is no need to, because there is enough material to build up two objects. Only as S perceives the battery in a different role, he sees the necessity for cooperation.
- S doesn't connect the battery to his object but just touches the object with the terminals and then puts it aside.
- S presents his object without the battery when asking the teacher for help. (He asks how that "thing" could be made to glow.)

He talks to his object and encourages it verbally to be active, and he calls it an electric circuit. As a necessity for an electric circuit he regards that all components are connected to a closed circle. He makes that sure. Now, that everything seems to be o.k., he pays attention to the battery.

Evidently S doesn't remember how to join the battery when he is first trying to, only the third attempt is correct. The first trial gives the impression that S has never heard about joining batteries. It seems to be only guided by the outer appearance of the battery - only one terminal is free, the other is fixed to the indicator. In the second attempt he seems to recapitulate fragmentarily a sentence learned during instruction. Now he takes off the indicator, leaves his circuit unchanged and tries to touch a contact-pin with both terminals.

The third trial, which comes a few minutes later, does not follow the goal to make his object work, but is caused by the question of a schoolmate. Now he acts without any insecurity. It may be concluded from the wording that he remembers and understands suddenly the advice of the teacher. From now on the battery remains part of the circuit, and S doesn't break this connection any longer inspite of the fact that his circuit still doesn't work. Although he is not able to join the battery at once and although no success is to be seen he recognizes that the connection is now correct - he leaves it unchanged in the following.

For the interpretation of these observations theories fit, which say that knowledge is context-dependant. These theories are e.g. advocated by Schütz and Luckmann and by Bauersfeld - the latter applying them to the learning of mathematics. Schütz and Luckmann say that the knowledge basis of the life-world is not a logically structured system, which is noncontradictory but an accumulation of typified units. As every action of life-world is submitted to the rule "first things first", each situation is only in a limited need for explanation. Thus inconsistencies between knowledge elements remain unconceived because they are alternately activated - their relevance depending on the circumstances. There are self-evidencies changing with the situations. The chance for recognizing inconsistencies of schemes and for modification only arises if they come into consciousness at the same time, that's to say in situations where the originally relevant scheme doesn't fit and therefore others are activated in addition. Here Schütz and Luckmann see the starting point for theoretical thinking.

Knowledge elements will be on different levels of familiarity, clearness, exactitude, and credibility. Schütz and Luckmann describe frameworks that determine the level, e.g. that of credibility. Although S possesses an adequate scheme to join the battery - this can also be seen in the written test the pupils did one week before, where he didn't fail in a single question - he twice activates inadequate ones in the above described situation. But he is able to recognize the right one

when it comes to his consciousness although no success is to be seen - the bulbs don't glow.

I'll turn now to S's idea that the bulbs "will not let pass through".

When circuit number 2c, which he thinks to be correct, doesn't work S wants to reduce the number of the bulbs to one. In this process he first happens to overlook the second bulb. When noticing this he recapitulates his idea "this bulb will not let pass through, damn'd" and removes it too. The fact that even the new circuit doesn't work makes him feel helpless - he wants to ask the teacher now - but doesn't call his idea into question.

Either the new failure cuts off all reflections on the problem or the above thesis is a theoretical conclusion on the basis of his conceptions about what goes on in the bulb. Then it would become possible that he didn't want to test the idea but just apply it to his construction.

For him his idea has a rather high level of credibility. This can be seen a) from the fact that he sticks to it although it is not successful and he is disappointed as it destroys his goal to build a circuit with more than one bulb, b) from his astonishment, when he sees the circuit of the neighbouring group and c) from his attempt to make them change their plan.

I interpret his idea as a theoretical conclusion, otherwise, as it did not come out as being successful in the experiment there would have been no reason for him to consider it so credible.

It's not possible to say more about the underlying concept but that S sees the bulb as a kind of sink or trap - not as a nonconductor - it lets something in but not pass through. Afterwards he never makes use of this view again. One year later in an interview he speaks of a circulation in one direction from one terminal of the battery through the bulbs back to the other terminal.

I want to add that S has come to the above idea after having tested a lot of others. It didn't organize his actions right

from the beginning. Two of the other three boys at the table adopted it as soon as the first difficulty occurred in their own circuit, only one objected to it. Afterwards S regards it as the mistake that the battery had run out of power. With that example I don't want to say that children's ideas are easy to change. Here there was a chance to because S had already passed through a lot of experiences which he activated in order to find the mistake so that he could get aware of inconsistencies. He had already limited the situation-parameters to a small number when he was confronted a) with the fact that bulbs in series do work and b) with a new reason for the failure.

#### References:

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### ELEMENTARY ELECTRICITY: AN EPISTEMOLOGICAL LOOK AT SOME EMPIRICAL RESULTS

Walter JUNG

#### 1 Introduction

One problem in learning physics - and I do not mean simply learning propositions of physics, or formulas, by heart - is that necessarily there is a prolonged "generative path" of the concepts and the theory, which should start with observable phenomena. There are always key-phenomena around which concepts and theories are organized,<sup>1</sup> and in general there is not one way to do this. Also processes of idealization play an important role in going from phenomena to theory. E.g., measuring the current intensity after doubling the length of a wire may exhibit half of the original intensity. But measurement will never yield that result to every decimal. Idealization is the first step in mathematization.<sup>2</sup> And again, in general there is not one way to do this. Some approaches prove to be useful, others lead to dead ends.

Processes of this sort, at the very beginning of the "generative path", alone would suffice to create serious learning difficulties. It is impossible to justify the choice of key-phenomena and the ways of idealization otherwise than by pointing to the success of the choices, either in coherently ordering phenomena, or in predicting phenomena, in using them in a calculated manner in technologies, or whatever may be your objective in doing physics.<sup>3</sup> And this success is by no means evident in the beginning.

I think this type of learning difficulties is unavoidable. But others are avoidable, and to these belong difficulties generated by mistaken choices of phenomena, by vagueness of reference, and by misleading meanings. I should like to discuss some examples, which can make understandable a lot of, mostly sad, results of investigations of what students

have learned, or not, by physics instruction in elementary electricity.

## 2. The Domain of Elementary Electricity: Meaning and Reference

### 2.1 Current

Within physics, "current" is a theoretical generic term. There is a closed simple circuit, you point to some observable phenomenon like heating or magnetic force, and add, a current flows through the circuit. This is the beginning of forming a theoretical concept. What is its reference, and what is its meaning?

First, it is a postulated entity, not directly observable. Somehow it refers to the circuit. I think that this vagueness of reference, apart from details of meaning, is one reason why students have difficulty in correctly answering questions of the sort:

Current is stored in the battery - Yes? No?

In Maichle's sample<sup>4</sup> 86% assented to this statement. In a sample of 64 students in a control investigation of my own (grades 9/10), 52% assented. (Percentages are rounded.)

In assenting, obviously current is no longer referred to the circuit. It is seen as an entity which can be here or there, be stored and at rest, or move, and also it can be used up. Thus in Maichle's sample 85% agreed with the statement:

The current stored in the battery is used up by an electric device connected with the battery.

A similar statement (with "bulb" instead of "device") found the approval of 50% in my control sample.

Now, I think that fixing reference is essential at the beginning, not only epistemologically, but also from the standpoint of physics: Generally, there is no meaning in

talking about current (in the sense of drifting charge) without a fixed reference frame. For example, "riding" upon the current transforms current to no-current. Thus at the beginning, the circuit should be used as the observable reference for talking about current. But there are different possibilities.

One possibility is to refer current to the circuit as a whole. It is one whole entity there in the circuit, similar to a running transport belt between battery and bulb.<sup>5</sup> But to speak of the current-in-the-circuit-there fosters the tendency to represent current as a substance which is, for instance, given by the battery.<sup>6</sup> Thus, when treating problems with branching, we frequently meet with errors by recurrence to this primitive notion of the current. It is a definite entity in the circuit, now split, and the bigger part goes the easiest way open to it.<sup>7</sup> E.g., in my sample 44% thought that the current in the main branch is the same after taking away the bulb in one branch. Many results of this type could be quoted. I do not think there is any one simple explanation. But I think that speaking of the current-there-in-the-circuit may be an important explanatory aspect not sufficiently discussed so far.

Another possibility of fixing reference is to refer current to every cross-section, or small part, or spot, even point, of the circuit. Thus we do not begin by speaking of the current, but by speaking of current events, or occurrences, here and there. Note that at the beginning we simply have no means to decide if something happens with the wire, or in the wire. For an analogy, think of heat conduction: we do not represent it as the drifting of some separate substance through the interstices of the wire, but of some affection, some "state", of the wire. Only much later we detect that current events can be found in spots of otherwise empty space, too. By referring to occurrences at different spots, we also avoid conceptual difficulties with

branched circuits, and we gain natural reference for the intensity of current as a local quantity. When referring current to the whole circuit, as in the analogue construction of the transport belt, there is danger that intensity is represented globally, as a sort of "bigness", as a quantity of a substance, reinforcing the representation of current as a sort of substance.

Of course, fixing reference alone is a weak way of defining a concept. So, what is the meaning of the term current? Again, there are many possibilities. To my mind, the most important move at the beginning of the "generative path" is fixing the right category, but avoiding too specific a meaning. For this is the appropriate strategy when generating a theoretical concept. It is generated as something of a certain type assumed from the observable circumstances, whose further properties and relations have to be explored.

An example of too specific a meaning is "electron drift". Apart from the fact that another theoretical term, electron, is invoked, which can give meaning to current only if some essential properties of electrons are already known,<sup>8</sup> it has the disadvantage of severe limitation when it comes to generalization, even with metals. Also it is apt to blur the distinction between current and charge, thus again reinforcing the intuitive notion of current as a definite substance, with possibilities of moving or being at rest, of being stored and used up. Also it brings the transportation problem in the foreground (energy transport vs charge transport), which cannot, to my mind, meaningfully be discussed at the beginning.

The advantage of assigning at the beginning the correct category, and not much more, seems to me an epistemological one: the concept is introduced as what it is, a frame

asking for being filled in by empirical investigations.

But this procedure has also advantages from the point of view of physics. (i) A student that has learned that current is not a substance, but an event, or occurrence, at every spot in the circuit, including the generator parts, should have difficulties in believing that current is stored in a battery. Occurrences are not the sort of things that are stored. (ii) He will be able to subsume any further development, from ion currents, to drifting holes, to displacement currents, even to matter waves. (iii) By fixing the meaning of "current" as "(electric) current event (or occurrence) at a spot in a circuit" we avoid associations of movement in this or that direction. It seems likely from many interview data that many students visualize the current as a sort of tide surging down the wire. It is exactly this following-up of the tide along the wire which prevents thinking functionally, e.g., when a new branch is opened. In a way this may also be called local reference. But it is a local reference which is moving with the current. And in fact we better call it "floating reference". (iv) Instead of stressing direction of movement and/or transportation, we stress what in fact can be observed, orientation (in the mathematician's sense).

By fixing meaning and reference in this way, we naturally lead students to ask, what are the properties of the occurrences at this or that spot? How do they compare? What are the conditions by which these properties can be manipulated? It is an issue of functional thinking in the first place, and not a transportation problem. Though it may seem paradoxical at first sight, fixing meaning and reference as some local occurrence does foster global, or better functional, reasoning.

Thus, the question of intensity naturally arises as a question of comparison between what happens here and there.



Within this setting, you never should think of the intensity of the current, but of the intensities of current events here and there. The first rule of elementary electricity frequently runs like, "The intensity of current in a simple circuit is constant." We know that many students are liable to transform this rule in, "The intensity of current is always constant", or "is constant" without qualifications, i.e. also in branched circuits. To give an example of the evidence, I quote from the stimulated recall interview of a girl (grade 9, Gymnasium), after having answered a questionnaire. She said, "I always use that rule" (i.e. current intensity is constant), as an explanation of answering "0,4A" for the intensity in each of two branches, where the intensity of the unbranched part is given as 0,4A. In Maichle's sample 48% answered in that way, and in my own 33%. I suppose that the rule, "The intensities of current events in every spot of a simple circuit are equal", is much less liable to this transformation.

In order to convey the meaning of "The intensities are equal", there should be exhibited phenomena which indicate it unequivocally. This is a case of choosing the right phenomena. Moreover, the student must know that the meaning of intensity of current events is something chosen, not given. E.g., students observe a hot part of a wire and a cool one, in the very same circuit: they simply have to be told that the magnetic force is the phenomenon chosen, and they have to see that it is constant all over the circuit.

In many teaching sequences this is a weak point, because frequently work begins with ammeters. But plugging the ammeter in here and there and observing an identical reading is convincing only, if you already are in possession of a rather developed concept of current. I was astonished when I learned from a highly intelligent student

(15 years) after the electricity lesson, that he answered a simple question of the type, "Given the ammeter reading, what is the intensity of current in the bulb?", by saying "One cannot tell exactly". In fact, all you can say is that the ammeter readings are the same everywhere. A measurement of the current intensity in the wires of the bulb had never occurred. Of course, we can improve the teaching situation by showing that the magnetic influence is equal everywhere, including the wires of a bulb.<sup>9</sup>

I cannot claim to having solved the problem of an ideal "generative path" of elementary electricity. But it seems to me necessary to state unequivocally that the investigations into physics learning are futile toil, as long as there is no consensus that two or three such paths are worthwhile, and no others. They have to be worthwhile from the point of teachability, and from physics, in the sense of not blocking the way of further learning. So far I do not see that an attempt has been made to achieve a consensus in these issues. Also it is unexplored how results about precepts and common sense frameworks influence the construction of such "generative paths".<sup>10</sup>

## 2.2 Voltage (Spannung)

Voltage is a difficult concept even for students at the university level.<sup>11</sup> There are a number of different meanings attached to the term in textbooks. But apart from meaning differences, I also find vagueness of reference. Mistakes of students arise from reference to spots (points) in the circuit, instead of (ordered) pairs, and also of "moving" locality. Thus, in my investigation 48% assented to the statement:

In a circuit there is voltage to be found at every spot (an jeder Stelle).

And 59% agreed with the statement:

Voltage is a property of the current at every spot in the circuit.

Again, in Maichle's sample 72% said "correct" to:

To make a bulb shining, intensity of current and voltage have to pass through it.

In my control investigation 25% assented to:  
Voltage is an occurrence.<sup>12</sup>

Though in general we found no high correlations between answering to these statements and problem solving behaviour, in this case we found evidence that frequently there is "local reference", or "moving locality", and respective meanings, in problem testing.

### 2.3 Resistance

Normally, learning difficulties concerning resistance do not arise by vagueness of reference. It is a concept which most clearly exhibits the dangers of giving meaning by analogy.<sup>13</sup> Even a simple theory of resistance shows that it arises from quite different sources. E.g., doubling the length of the wire, all else being equal (U, cross-section, material), leads to lowering I, not because of any change in "holding back the current", or in producing greater "friction", and similar analogical representations, but simply because the field E is only half now.

Let me go a little deeper into the details of arguments that could be observed with teachers, and sometimes textbooks. The wire of double length "doubly resists the flowing of the electricity just as" - the analogical reasoning - "a longer waterpipe resists the streaming of water."<sup>14</sup> Note the extreme vagueness of reference of the term "the electricity". Put a little different, the argument is, "the longer wire more strongly resists the current, just as ..." Is it the current as an entity in the whole wire? Well, then "resistance" (in analogical meaning, i.e. frictional force) is "doubled". But then "the" current has been "doubled", too. "The" original current - the part in the original wire - experiences exactly the same

"resistance" (friction). What has changed, in fact, is the field, i.e. the electrical analogue of the pressure gradient.

Similar misconceptions arise when teachers try to explain why resistance is doubled by connecting in series two equal bulbs, and phenomena by connecting in parallel. If there is that vagueness in reference of the term "the current", it can easily be argued that by adding a parallel branch, the resistance (i.e. friction) against the current is again stronger. Thus, e.g., in the aforementioned stimulated recall interview with a girl, she explained, "if you take off one (bulb, in a parallel branch) ... there is less resistance then" - I can easily feel with her! Thus the analogical meaning must be highly confusing for younger, and - as is well known to academic teachers - even for mature students.

I should like to add two remarks in finalizing this paper.. First, we have little hope to correctly teach physics to students, if teachers harbour misconceptions by themselves. Research has widely neglected to explore representations of physics knowledge in teachers.<sup>15</sup> Second, elementary electricity should be taught as a rich domain in its own right. Mechanical analogies are dangerous, as has been noted by a number of researchers. But there is another aspect which should not be forgotten: It may often be as easy to find electrical analogies for mechanical processes as the other way round, if only we would get used to it.

### Notes

- 1 I do not want to discuss philosophical questions here. Yet discussions within the philosophy of science begin to influence science education, see, e.g., J. Nussbaum, Classroom Conceptual Change: The Lessons to be Learned from the History of Science. In: Proceedings of the International Seminar Misconceptions in Science and Mathematics. June 20-22, 1983. Cornell University, Ithaca, N.Y., USA, p.272-281. Also, W. Jung, Aufsätze zur Didaktik der Physik und Wissenschaftstheorie. Frankfurt a.M. 1979

- 2 Idealizations of percepts are a version of what I.Kant called "schemes", as instruments for correlating (mathematical) concepts and sense experience, see Critique of Pure Reason, I, pt.2, sec.2, bk.2 (Von dem Schematismus der reinen Verstandesbegriffe.)
- 3 Time and again researchers in science education fix attention upon one, mostly fashionable, objective. But we have to take account of the fact that not only does change the "image of science" (Elkana) from epoch to epoch, but that different images coexist in one epoch. This is of educational relevance because of the interrelation of motives and objectives.
- 4 Students mainly from grade 8, Realschule, sample size  $N = 273$ .  
Here I present the results of her lowest ability group only in order to secure comparability with my control investigation. A complete analysis of the Maichle data will probably be available early in 1985. Maichle has presented some of her results reported here within a different interpretative framework, see U.Maichle, Representation of Knowledge in Basic Electricity and Its Use for Problem Solving. Proceedings of the International Workshop on Problems Concerning Students' Representation of Physics and Chemistry Knowledge, Sept.1981, Ludwigsburg, 174-193. There, and also in her dissertation, she has reduced the sample for reasons which do not concern us here.
- 5 This is the conception of H.Härtel, IPN, see: "The electric circuit as a system" in these proceedings.
- 6 There are many evidences of the tendency of younger students to think that the battery delivers a characteristic and constant current. Thus, in Maichle's sample 36% agreed with the statement: The intensity of current is given (determined) by the battery alone. In my control sample the percentage was 34%. We frequently heard this opinion also in interviews. Also Schmidt found this tendency marked in his detailed investigation, D.Schmidt, Schülervorstellungen zum elektrischen Stromkreis. Examensarbeit, Univ.of.Bremen, 1983.
- 7 This notion is frequently found, also in interviews. My hypothesis is that the idea is reinforced by the way teachers handle shortcut phenomena.
- 8 This course is possible if one begins with electrostatics.
- 9 A pilot study of a course constructed upon these principles had an ambivalent result. Further investigations are needed and are in preparation, see W.Jung, H.Wies-

ner, I.Kiowski, E.Weber, Zum Anfangsunterricht in der Elektrizitätslehre. In: physica didactica 9 (1982) 257-272. An earlier version of the course is expounded in, W.Jung, Elektromagnetismus für die Sekundarstufe I. Frankfurt a.M. 1981.

- 10 Various possibilities have been discussed. The main alternatives seem to me these:
  - (i) Structuring the course according to the principles of the subject matter, i.e. physics, and taking account of "preconcepts" by changing teaching methods, e.g. by opening contrasting discussions.
  - (ii) Changing the structure of the teaching sequence itself, e.g., by beginning with electrostatics, i.e. charge, or by relying on the intuitive energy concept (the "using-up" aspect of current), and similar moves.
- 11 See my paper, An Example of the Speaking-aloud Technique, this conference. In the textbook literature the following meanings can be found:
  - (i) Voltage = Potential difference, which limits voltage to electrostatic fields.
  - (ii) Voltage = EMF
  - (iii) Voltage =  $P/I$
  - (iv) Voltage  $U = I R$  (also "voltage drop").
- 12 The rationale of category questioning is explained in my paper, Category Questionnaires - The Technique and some Results, this conference.
- 13 Different strategies of meaning endowment are discussed in chpt.3.2.9-10 of, W.Jung 1979 o.c. Results of investigations into analogical meaning endowment are reported in: H.Schwedes, P.Schilling, Schülervorstellungen zum Wasserstromkreis, in: physica didactica 10 (1983) 159-170, and D.Gentner, D.R.Gentner, Flowing Water or Teeming Crowds: Mental Models of Electricity. In: D.Gentner, A.L.Stevens, Editors, Mental Models. Hillsdale (New Jersey), London 1983, 99-130.
- 14 Example from a textbook, R.Götz, Physik, Arbeitsbuch für die Hauptschule, Freiburg i.Br. 1969, p.112.
- 15 The investigation of R.Cohen, B.Eylon, U.Ganiel, Potential Difference and Current in Simple Electric Circuit: A Study of Students' Concepts. Am.Journ. of Physics 51 (1983) 407ff, has looked into physics knowledge of teachers, too.

Please note: This is an abridged version of the original paper, which can be got from the author.

# CHILDREN'S INTUITIVE IDEAS ON ELECTRIC CURRENT AND THE MODIFICATION OF THOSE IDEAS

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## INTRODUCTION

Recent research into children's ideas has shown that certain strongly held children's conceptions can be at variance with scientific conceptions, and that they can remain uninfluenced or be influenced in unanticipated ways by science teaching (see, for example Driver and Erickson, 1983). Where these alternative conceptions are retained in place of certain scientific concepts which are of fundamental influence to subsequent understanding of scientific ideas, they will prove a stumbling block to subsequent learning. For example, a child's non-scientific conception of electric current could inhibit subsequent learning about electrical circuits (Shipstone, 1982, 1984). Such findings raise questions about the need to change children's ideas, how best to attempt to change children's ideas, and how effective new approaches can be in affecting change.

The desirability of changing children's ideas is discussed elsewhere (Driver, 1982; Osborne, 1982), and there has been much recent discussion as to how best to change children's ideas (Strauss, 1981). The work of Hewson (1981a, 1981b), Erickson (1979), Renner (1982), Karplus (1977), Nussbaum and Novick (1981, 1982), and Barnes (1976) as well as our own work (Osborne, 1982 and Osborne and Wittrock, 1983), has led us to view certain factors as likely to be important in changing children's ideas (Cosgrove and Osborne, 1985). These include the need for

- (i) teacher preparation in terms of both pupil and scientific views,
- (ii) familiarisation of pupils with situations which provide a context for the ideas to be discussed,
- (iii) recognising, clarifying, and making explicit by pupils their own views through words or pictures,
- (iv) appreciation by pupils of the views of others,
- (v) critical experiences to challenge the status of presently held views, and
- (vi) extended opportunities for pupils to experience the usefulness of the scientific perspective.

As a consequence of these needs and the research cited above, we have developed a teaching sequence for a set of lessons designed to achieve conceptual change (Cosgrove, Osborne and Tasker, 1983). The

sequence consists of three phases; a familiarisation phase, a challenge phase, and an application phase. We will exemplify and elaborate the model in this paper using our work on the topic "electric current".

#### ELECTRIC CURRENT

Over the last few years a major focus of our work has been the topic of electric current. Interviewing of children in the U.K., N.Z. and U.S.A. (Osborne and Gilbert, 1980; Osborne, 1981, 1983) has led us to propose that there are four main ways in which pupils conceptualise current flow in a simple electrical circuit (Figure 1). The prevalence of these views is indicated in Figure 2, although our open-ended interview work suggests that where alternatives are not presented to children an even greater percentage of younger pupils describe electric current as flowing toward the bulb in both wires (Model B), while Model C is a very common view with older pupils. These results are largely in agreement with studies in other countries using different investigating procedures (Tiberghien and Delacote, 1976; Andersson and Karrqvist, 1979; Russell, 1980; Fredette and Lochhead, 1980; Norman and Clement, 1981; Shipstone, 1982, 1984 and Cohen, Eylon and Ganiel, 1982).

On the basis of our knowledge of children's ideas about electric current we have designed a set of lessons to change children's ideas based on the three phase teaching sequence mentioned earlier.

In addition to recognising the need to prepare teachers about the views of children and scientists on this concept, the teaching model consists of

Phase I - Familiarisation Phase - Learners are provided with many experiences involving simple electrical circuits, usually of not more than one or two cells, one or two lamps, a switch and assorted wires. As the students become familiar with constructing and using simple electric circuits, the teacher begins to focus the learners' thinking on the electrical happenings in the circuit. The aim here is to raise questions and promote discussion in a specific context.

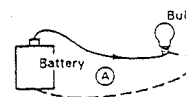
Phase II - Challenge Phase - Children's views about current flow in a circuit are evoked from the pupils and made public. Students with different views work in small discussion groups. Through this work and class discussion a critical test of the different models is developed. Predictions from the various models are made and tested (Figure 3). We call this the critical lesson.

FIGURE 1: Survey Question about Electric Current

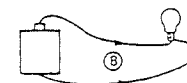
#### "ELECTRIC CURRENT CAUSE A LIGHT BULB TO GLOW"

A battery is connected to a torch bulb as shown in the diagram. The bulb is glowing.

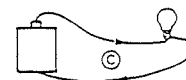
In the way you think about it, the electric current in the wires is best described by which diagram?



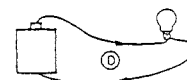
There will be no electric current in the wire attached to the base of the battery.



The electric current will be in a direction toward the bulb in both wires.



The direction of the electric current will be as shown. The current will be less in the "return" wire.



The direction of the electric current will be as shown. The current will be the same in both wires.

FIGURE 2: Survey Results from the Question of Figure 1

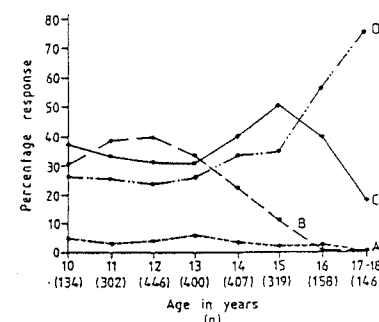
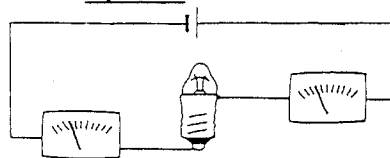


FIGURE 3: Ammeters in a Circuit Provide a Critical Experience



From this experiment many questions are raised. To many children, Model D is not sensible because they do not yet distinguish between current flow (the energy carrier) and energy changes. Analogies are introduced to help understanding, and to develop confidence.

Phase III - Application Phase - Children are presented with a series of practical problems to solve. These include making a set of traffic lights, simulating circuits to ring bells, illuminating hallways and corridors, controlling car heaters and running motors. Problems are chosen where a scientific view of current flow will help in solving the problem and in understanding the solution.

The development of the above teaching model for electric current involved the work of an action-research team of practising teachers who met during 1982 in New Zealand, the production and subsequent discussion with many teachers of a video-tape of a teacher teaching the challenging phase (Osborne, Tasker and Schollum, 1982), as well as the use and monitoring of the teaching sequence in a range of classrooms. This work resulted in a teacher's guide and associated pupil workbooks (Cosgrove and Osborne, 1983).

#### RESEARCH INTO LEARNING

Faced with describing what happened when the approach was used we needed to consider what was to be described and how it was to be described. In our view we needed to describe:

- (i) The ideas about electric current that children bring to the series of lessons, and the short-term and long-term influences of teaching on these ideas. (Interviews, and surveys of the type shown in Figure 1, were considered appropriate here).
- (ii) What actually occurs in the classroom in terms of what is taught, why it is taught, what is learnt and why it is learnt. (We see no alternative but case studies involving naturalistic classroom observations (Tasker and Osborne, 1983) to explore in depth what occurs in the classroom).
- (iii) The views of both teachers and pupils toward the series of lessons. (Interviews and open-ended surveys to gauge the value ascribed by pupils, and teachers, to the various aspects of the lessons and to establish reasons for these viewpoints).

#### FINDINGS

Over the last two years (1982-1984) a range of teachers and classes have been studied as they used the approach.

In this paper we will focus on a group of 15 eleven year-old children of average to above average ability, eight boys and seven girls. These pupils were taught by this approach in June-July 1982, and we have been able to follow them since that time. The findings from this study that we will focus on are ones that we have been able to corroborate in our observations of other classes, pupil interviews, and teacher interviews.

Familiarisation Phase - The familiarisation stage certainly provides children with the opportunity to become familiar with simple electrical circuits. Undoubtedly pupils come to these lessons with a wide range of experience, or lack of experience (Kelly, 1981). However, the focus questions which activate children to think about what is happening in the wires does not lead to pupils developing a scientific view of electric current; nor would we necessarily expect them to.

Following the familiarisation phase, pupils are asked about the current flow in the simple D.C. circuit (Figure 1). The results so far suggest that class interaction leads to changes in viewpoints; pupils are more likely to be found clumped together into one or two viewpoints, typically B and C. For example compare the following percentages for the class of 11 year-olds, when they had just finished the familiarisation experience, with a representative sample who had not been taught the topic (Table 1).

Table 1: Percentage Responses Immediately Prior to the Critical Lesson

| Percentage Responses    |              | Model Chosen (see Figure 1) |    |    |    |
|-------------------------|--------------|-----------------------------|----|----|----|
|                         | 11 year-olds | A                           | B  | C  | D  |
| Representative Sample   |              | 4                           | 38 | 32 | 26 |
| Case Study Class (N=15) |              | 0                           | 7  | 86 | 7  |

This information, along with information from other classes, suggests that children will not come to a Model D view of current flow simply from first-hand experience of simple circuits. However, through continued interaction they may come to an agreed view within their own group.

Challenge Phase - Initial teaching on a one-to-one basis (Osborne, 1983) suggested to us that pupils accepted the meters, and what the readings on the meters implied, even though they found this difficult to explain. However, in the classroom, peer interaction seems to result in less immediate acceptance of model D. Pupils need to be convinced that the meters do not perturb the system. They argue about what the meters are in fact reading, and any slight random errors or discrepancies are used to sustain the original pupil viewpoint.

Nevertheless, a measure of which model of Figure 1 is preferred just after the discussion, debate, and experiment shows that many pupils are prepared to at least acknowledge model D (see for example Table II).

Table II: Percentage Responses After the Critical Lesson

| 11 year olds | Model Chosen (refer Figure 1) |   |    |    |
|--------------|-------------------------------|---|----|----|
|              | A                             | B | C  | D  |
| Class (N=15) | 0                             | 0 | 14 | 86 |

Application Phase - In interviews with children who have been involved in the lesson sequence we have found that the application phase can have a considerable impact on pupils. For example, for the class of eleven year-olds, extended interviews eight months later with six children chosen at random established that each child considered the problems were the best things about the lessons. And six further interviews with these children two years later established that these views had not changed.

#### REGRESSION OF IDEAS

While children appeared to change their views following the critical lesson, subsequent monitoring showed that over a period of time there was a regression of ideas away from model D. (See Table III.)

Table III: Percentage Responses Compared Over Time

| Class of 11 year-olds (N=15) | Model Chosen |    |    |    |
|------------------------------|--------------|----|----|----|
|                              | A            | B  | C  | D  |
| Before critical lesson       | 0            | 7  | 86 | 7  |
| After critical lesson        | 0            | 0  | 14 | 86 |
| 1 year later                 | 0            | 13 | 40 | 47 |

An in-depth study of six randomly chosen children over two years following the teaching experience, without any further teaching on the topic, shows how the children tended not to have an absolutely stable view. When asked about slightly different current configurations and different problem situations they tended to vacillate to some extent; often between model D and model C (shown as D/C in Table IV). This effect has been observed in our other studies.

Table IV: A Study of Six Children's Responses to the Electric Current Models of Figure 1

| Child   | Model favoured                                              |                           |                                   |                           |
|---------|-------------------------------------------------------------|---------------------------|-----------------------------------|---------------------------|
|         | July 1982<br>before-after<br>critical lesson<br>(interview) | April 1983<br>(interview) | November 1983<br>(written survey) | April 1984<br>(interview) |
| Inger   | C D/C                                                       | D/C                       | C/D                               | D                         |
| Sylvia  | C D/C                                                       | D                         | D/D                               | D                         |
| Karen   | C D                                                         | C                         | B/C                               | C                         |
| Stephen | C/D D                                                       | D/C                       | D/D                               | D                         |
| Mark    | C D                                                         | D                         | C/D                               | D                         |
| Adrian  | C D/C                                                       | D                         | D/D                               | D                         |

Further insight into the learner's problems are provided by the following interview with one other pupil from the case-study class.

Interviewer: Do you remember these Models? [Figure 1]

Vanessa: Yes.

Interviewer: Which way do you think about electric current?

Vanessa: At first [before she was taught] I thought it was Model B. Because I didn't realise that if it was B the battery would go flat very soon [this is something she had decided herself or with peers]. So now I think Model C is best ... quite a bit of current comes into the bulb, and some of it is wasted up ... it can't take it all at once so some of it takes it back.

Interviewer: Did you [when you were taught] do the thing with meters?

Vanessa: Yeah, we found Model D works with the meters ... but I don't understand D ... I know it works but I don't understand how it works.

Interviewer: Did your teacher discuss it?

Vanessa: Yes and I kind of knew how that went ... it made sense a little bit ... but afterwards I thought of some other ideas ... "How did that work?" "What happened?" and "How did he explain ...?" ... I got muddled up ... If you are not using any power in the bulb how is it going on? I understand C.



These results are confirmed by our other studies. While there are some pupils who have difficulty in accepting that the meters do not change the physical situation, or find some confusion in understanding the current direction indicated by the meters, most pupils will initially accept that the meters confirm Model D. To tease out the differences between energy transfer in the circuit, and current flow, analogies need to be introduced. All analogies have difficulties and pupils often tend to interpret analogies so that they fit their original ideas (often that electricity is used up in the bulb) and at the same time account for the meter readings (Gauld, 1984). At present one of our major research thrusts is to explore possibly useful analogies and the pupils' interpretations of these analogies. Finally, there is the problem of ensuring that in our Application Phase the pupils do use their models for predicting a solution rather than pupils attempting to solve the problems using trial and error.

#### WIDER ISSUES

Our research on electric current tends to confirm the difficulties of changing pupils' ideas toward the views of scientists, and we are involved in on-going research on this topic. However, the research to date, particularly our observations of classrooms using the approach, raise some wider issues.

We are encouraged by the way children have been prepared to discuss their views, to listen to the views of others, to attempt to relate their own ideas to experimental evidence, and to various analogies, which they invent or learn about. These activities, we consider, have value whether or not the model of electric current that a pupil finds sensible and useful is the scientists' view. Nevertheless this issue raises the need for considered debate about the aims of science education.

We are also increasingly aware that conceptual change takes time, and that it is important that counter-intuitive ideas are reconsidered at regular intervals over a period of time. This has implications for curriculum design.

Finally, our research reaffirms to us the very central importance of children understanding basic electric circuit concepts for on-going learning in physics. Without a Model D view of electric current the development of more advanced scientific concepts associated with circuitry must be problematic.

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# USING PRACTICAL AND TECHNOLOGICAL PROBLEMS TO PROMOTE CONCEPTUAL CHANGE

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## TECHNOLOGY AND PHYSICS EDUCATION

We live in an increasingly complex technological environment. If science teaching is to be meaningful and valuable, then it is desirable that our students can relate what they are taught to the world outside the classroom. Teachers can help students by using technological contexts and examples when developing principles, experiments, problems and examination questions.

Unfortunately, our experience indicates some reluctance by teachers to refer to technology. The following are some of the reasons:

1. It is easier in examinations to ask abstract questions, and to set problems devoid of reality, than it is to find real life contexts for questions.
2. It is easier to relate physics principles to the artificial world of the physics laboratory than to real life applications.
3. Teachers have very limited resource material available to show them where, and how, the principles of physics relate to the technological applications of industry, home, hospitals and other everyday situations.
4. Some students seem to prefer physics to be about an abstract, idealised world, uncontaminated by the complexities of reality.

In our view, a prime aim of science education is to help learners to make better sense of their world (Symington, Osborne, Freyberg and White, 1982). Our thinking has been influenced by constructivist ideas on learning (Piaget, 1929; Kelly, 1955; Wittrock, 1974; Claxton, 1984). A constructivist viewpoint contends that it is important that learning should build on the learner's ideas, so that the learner is able to develop an integrated view of the world: such a view should ideally relate comfortably to the present ideas of scientists, and to the technological and natural worlds in which the learner lives (Osborne and Wittrock, 1983). Implicit in this argument is the notion of

enculturation (Papert, 1981; Gardner, 1984). Papert asks how children can learn mathematics in our society which is alienated from mathematics, whereas Gardner notes that the Japanese, by immersing children in music, produce, at the least, competent musicians. We contend that an appropriate culture for physical science concepts is the technological world. An additional point is raised by Fensham (1981). He considers that the school science curriculum is either too intellectual ("heads" science), or too peripheral or transitory ("hands" science) whereas it could be made more practical ("hands" science).

Some material is available (e.g. Jones 1982) to help teachers relate the ideas they teach to the technological world outside the classroom. However, these materials often require adaptation for classroom use. What may well be required is much more specific material, particularly for science programmes in which non-specialists are faced with teaching physics, as in the junior high school.

#### PROBLEM SOLVING

Most physics teachers and practising physicists, we think, would consider that an essential part of physics learning is developing the skill and ability to solve problems. Typically, the problems found in most introductory physics books require for solution the recall of a formula, rearrangement of the equations involved, then substitution and calculation. Certainly this is the approach used by many novices, according to Larkin and Reif (1979), Larkin (1983), Kempa and Nicholls (1983), and Arons (1981, 1982).

However, these researchers argue that this is not the way that physicists go about problem-solving. The proficient physicist adopts a three-stage approach. The first stage is much the same as that of the novice, inspecting the statement of the problem. The second stage is quite different. Instead of reaching for a formula, the proficient physicist attempts to think about the problem qualitatively, to develop a feeling for the problem, to see if it makes sense; in other words, he or she re-organises and re-structures the information. (Sketches, and flow diagrams, are commonly made.) It is only when the problem is understood qualitatively, after it has been allowed to rub up against the common-

sense view of the physicist, that he or she proceeds to the step of selecting a suitable formula. Qualitative reasoning, then, is the process of shuffling one's concepts about in order to bring them to bear upon a particular problem, whether it be from a textbook, or from the technological sphere.

This view leads us to consider that qualitative problem-solving is an important skill that learners should develop as an explicit part of school science. It need not be dependent upon mathematical skills and techniques, and therefore it could be developed at a relatively young age.

#### THE PLACE OF TECHNOLOGICAL PROBLEMS IN OUR TEACHING APPROACH

In our earlier paper (Cosgrove, Osborne and Carr, 1984) we have described a three-phase teaching sequence to promote conceptual change and development, and we have exemplified this with respect to the topic of electric current. In that paper we emphasized the second or challenge phase, but pointed out that this phase should be preceded by a familiarisation phase, and followed by an application phase.

The ideas that we have about a three-phase teaching sequence for conceptual change, about the importance of technological problems, and about qualitative reasoning have led us to set the activities of the familiarisation and application phases of our teaching scheme for electric current in the context of qualitative technological problems.

In the remainder of this paper we will describe some of the problems we have used with 8-14 year old pupils, sometimes in the familiarisation phase, but more frequently in the application phase, and discuss the prospects and difficulties of using such problems with children. A summary of this approach is contained in Table 1.

In addition to the six problems listed in Table 1, we have used several others: a binary call code, a lighting system for a mine, and controlling the heater in a car.

Table 1: A technological problem-solving emphasis to the development of the concept of electric current using the generative teaching model.

| <u>Phase 1</u>                                                                                                           | <u>Phase 2</u>                          | <u>Phase 3</u>                                                                                                                                                           |
|--------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Familiarisation                                                                                                          | Challenge                               | Application                                                                                                                                                              |
| Empirical solution to problems                                                                                           | Critical Tests                          | Predicting solutions using theory.                                                                                                                                       |
| <ul style="list-style-type: none"> <li>. Xmas tree lights</li> <li>. Railway tunnel</li> <li>. Traffic lights</li> </ul> | Devise a theory to describe the current | <ul style="list-style-type: none"> <li>. Front and rear door alarms for a house</li> <li>. Car indicator lights</li> <li>. Changing speeds of electric motors</li> </ul> |

One problem which provokes considerable interest, which we use in the first, familiarisation, phase is that of monitoring whether or not there is a railway train in a long tunnel (railway tunnel problem). Using equipment from a model railway set, and selecting rolling stock with metal wheels and axles, children can, in a short time, devise a circuit which satisfactorily detects a train. It is likely that the learner will be successful. The teacher can then use the learner's circuit to focus attention on one or two additional points. The first point is to encourage the students to explain the circuit, first in terms of the answer produced, and then in terms of the learner's view of electric current. For some students, the teacher might suggest that they think further about the circuit. For example, the teacher might ask (about Figure 1) "What would happen if the lamp should fail?" Often, though, students will recognise that this simple circuit has drawbacks. Students will enquire about the lamp and the cell failing, and whether the train is in the tunnel or some distance away. Improvements are made, and a system like that shown in Figure 2 can be invented by many pupils.

Some students become dissatisfied with these "improvements", as they consider such issues as a derailment. As a result, students reject electrical solutions, and propose others; for example, television monitoring, with the associated advantage of knowing which wagons were part of each train.

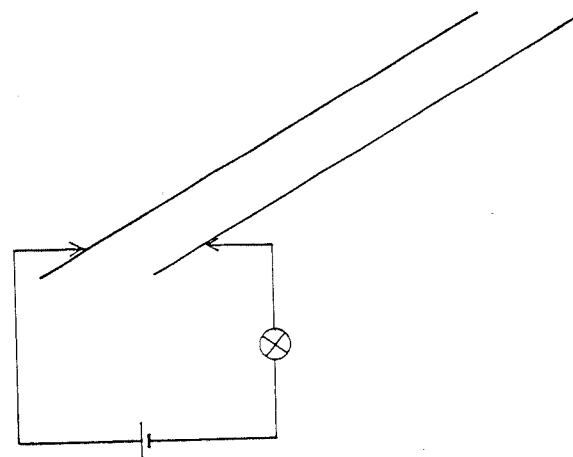


Figure 1 - A simple solution to the tunnel monitoring problem

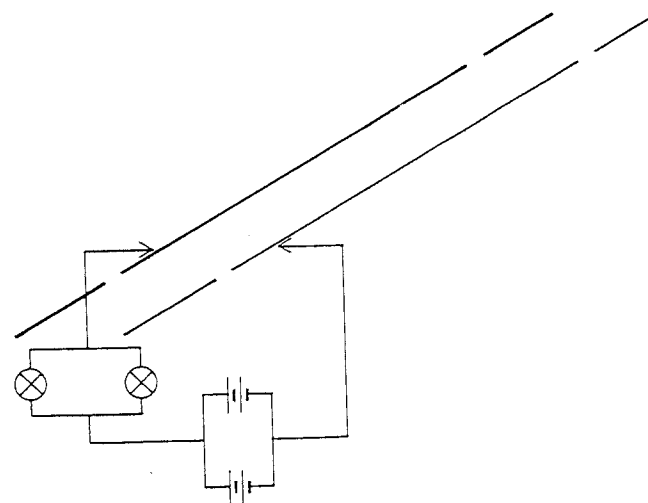


Figure 2 - Advanced solutions to the tunnel monitoring problem

# AN EXAMPLE OF A CHILD'S THINKING ABOUT A TECHNOLOGICAL PROBLEM

We will now exemplify the impact of the problems on children's thinking using one case study. Stephen had been in a class where these electric circuit problems had been provided. One of us interviewed him two years later. The transcript from this interview indicates Stephen's reactions, and the impact that the technological problem solving approach had on him.

Int: What can you remember about the set of lessons on electric current?

S: The "visitor at the door" problem was one that interested me although it was not my favourite. I can remember ... we had to figure a way of having two doors and two door bells, and a light related to each one. .... If the front door bell rang, and if a deaf person was suddenly to come in to a room with the two lights, it would show that a door bell would be ringing, and which one.

Int: Can you remember your answer?

S: Well, my first answer was to use two batteries.

Int: Could you draw again what your answer was?

Stephen's drawing is reproduced in figure 3.

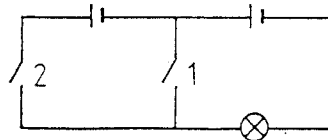


Figure 3 - Stephen's circuit

Int: Can you explain what you have drawn?

S: Well, in this circuit, ... if switch 1 was being activated it'd only use the power of the one battery for the light bulb, therefore it'd be fairly dull. But if switch 2 had been used, both batteries would be incorporated to power the bulb, therefore it would be brighter. And so there would be a difference between the two doors.

Stephen was asked about his explanations for this proposal.

Int: What's happening? (with switch 2 closed)

S: The flow would be increased by a very little amount. But the main thing would be that more fuel would be circulating to power the bulb.

Then Stephen told the interviewer about another solution he had proposed. He was asked to draw his solution and he quickly sketched the circuit shown in figure 4.

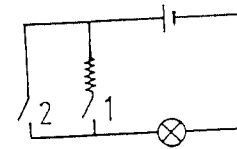


Figure 4 - Stephen's second version

Int: What is that thing there? (Pointing to the resistor symbol)

S: It's the resistor, or high resistance wire. It does the same job.

Int: What do you mean "it does the same job?"

S: Well, they cut down on the flow of electricity.

Int: Describe what you've drawn.

S: Well, here, using only the one battery, if switch 2 was operating there would be a normal flow of current from the battery to the bulb, and back to the battery. But if switch 1 was activated, when going in the circuit it would meet the resistance from the high resistance wire, or the resistor, and it would slow down the current, and therefore less fuel would be fueled onto the light bulb.

Int: What would happen to the light bulb?

S: It'd go duller.

Int: What do you think is going on in the resistor?

S: Well, some metals don't pass electricity very well.

The interviewer recalled that, two years earlier, Stephen had constructed this circuit using the spring (of stainless steel) from the retracting mechanism of his ball-point pen as the resistor.

Int: How does that happen?

S: Maybe different metals might have been fused in, or melted in, into the wire ... And when the flow would be coming through it is a bit like having a whole lot of stakes, or a couple of walls in a river, not completely cutting off the circulation, but just slowing it down. That'd be how it works.

Int: Do you think the light bulb is a resistor?

S: It shouldn't be.

While we would acknowledge that Stephen did not hold views that are identical with those of physicists, it is clear that his notions are moving towards those of physicists, and that his ideas make sense to him.

However, more importantly to us the episode of dealing with these problems was still vividly clear to him. This is not an isolated instance and it is our experience that students are able to relate to, and remember clearly, problems based on the technology of the familiar world.

#### RESULTS OF USING THE APPROACH

When we have interviewed pupils some months after they have been taught, using the three phase teaching approach (Table 1), the aspect of the lesson which these pupils most vividly remembered was not the critical lesson, or the specific challenging of their models of electric current using the meters (see Cosgrove, Osborne and Carr, 1984). Rather they referred to the technological problem-solving features of the lessons.

With 11 year olds there was much enjoyment, as in these responses to an interviewer's questions.

"The best thing was finding out how you make the traffic lights, the puzzles." (Karen).

"I like the things like the deaf man's door bell, and the traffic lights. The traffic lights are the best." (Inge).

"And the problems, they were fun to work out." (Sylvia).

Sylvia was able to explain some of the satisfaction she felt in this way (about the traffic lights problem):

"After we had worked it out on paper we would never have known if it had actually worked. There might have been something wrong with just the planning of it. It was quite a difficult problem but we managed to get it going."

Older students reported other satisfactions.

"Yes, they were good activities in that you had to find your way through them yourself, and find out which was the best solution ... which was the quickest, the easiest. And I think you did end up finding your own answers ... which I think is good ... it wasn't just all fed to you." (Justine, 14 years).

"He gave us that Xmas tree one ... so my friend and me we did it together ... worked it out ... I reckon just being given the problem and having to work it out yourself, I like doing that." (Donna, 14 years).

Several of these technological problems suggest on-going projects which have been accomplished by pupils and displayed in classrooms, and at school science exhibitions.

While it is possible to report that, for many youngsters, this technological approach to learning science has made a lasting impression, we do note some difficulties. One concern, in terms of the application of our teaching model (Table 1), is in achieving a situation in which students will make predictions and do some planning before they resort to a trial and error approach.

A second concern relates to the behaviours of teachers. For some, the teacher's role is to take students on a tour of the subject, presenting it in a text-book fashion with little reference to the real world outside the classroom door, despite our specific suggestions. For these teachers, frequently non-physics specialists, the teaching task has been achieved as soon as the concept has been confronted (challenge phase of Table I). In our view, very little conceptual change occurs without a process of stabilisation (the application phase of Table I). We have to find ways for these teachers to understand the value of the application phase and the usefulness of qualitative technological problems for pupils. Our work in teacher-education suggests to us that such teachers need to be taken through the approach themselves before they become enthusiastic about it.

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## USING COGNITIVE CONFLICT TO TEACH ELECTRICITY

Jean-Louis Closset

## Introduction

It is not actually a new idea to use cognitive conflict in teaching. But electricity is perhaps one of the best fields to try this method on account of the great facility of manipulations in this domain. We'll give some instances of situations useful to create a cognitive conflict and we'll describe the particular way we use questions from our research work about sequential reasoning (CLOSSET 1983; 1984) to teach a "system view" of the electric circuit.

But a more relevant question about cognitive conflict has to be examined: what can we hope using cognitive conflict and why is it so difficult to succeed. Thus our intention is also to develop briefly a critical point of view about cognitive conflict and to suggest some other ways to use it.

## Using cognitive conflict

To use cognitive conflict is to put the student in such a situation that his own ideas are inconsistent with experimentation or with logic. One hopes then the student will change his mind and adopt a more "correct" view. Thus the first condition to use cognitive conflict is the knowledge of student's ideas. In this respect electricity is also a good field.

Reasoning in terms of "constant current" is a well-known student's reasoning (MAICHLE 1981; CLOSSET 1983a). To test this we can propose a circuit with two similar bulbs in parallel (fig. 1) and first ask for

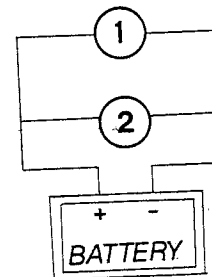


Figure 1: two bulbs in parallel

a prediction about the brightness of the bulbs. Generally the answer will be: "same brightness, bulbs are similar and the current is divided in two equal parts". But one can also find this answer (induced by the particular topology of the circuit): "bulb 1 will shine dimmer than bulb 2 because bulb 2 take the part of current it needs and bulb 1 will receive the

rest". In this last case a cognitive conflict can be created without experience, it's just necessary to show that the positions of the two bulbs are equivalent. If the student agrees, he will give the first answer. It is a correct answer, but this answer is also consistent with a "constant current" model of the battery. It's possible to see that asking: "what happens with the brightness of bulb 2 if bulb 1 is taken off?" A frequent answer is: "bulb 2 will shine twice as much as before because it will receive the whole current". Now a cognitive conflict can be created by experimentation.

Sequential reasoning is another very frequent reasoning students use, with or without conservation of current flow ( SHIPSTONE 84; CLOS-SET 83a ). One can show it with this question about the circuit of the figure 2: "In this circuit bulbs 1 and 2 are similar and R is a resistor.

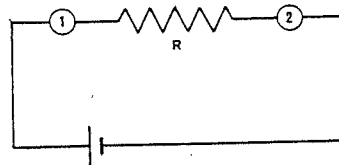


Figure 2: a question to create cognitive conflict.

#### Not so wonderful.

In our teaching (university level) we used this last situation and we reinforced the effect by increasing the resistance and asking for a prediction about the brightness of the two bulbs. This must lead, we hoped the students to adopt a "system view" of the electric circuit. But it's not so evident like we can see if we try to this "system view" with the following question about figure 3: "The black box contains a circuit with only wires, bulbs and batteries. We want the brightness of bulb 1 to be the same as the brightness of bulb 2. Can this happen in all cases, in no case or only for some particular circuits in the box?" Still 33% of our students who are able to give a correct answer to the questions with a resistor, answered to this question: "It isn't possible in all cases" with comments like this one: "The brightness of the bulb 2 will be smaller than the brightness of bulb 1, so we have to add a battery in

the black box to compensate the lack of flux of electrons due to the first lamp".

It seems that some students who are forced by experimentation evidence to accept the correct answer to the questions with a resistor don't deduce from this a general "system view" of the circuit. That stands to reason that it isn't the same to accept a different

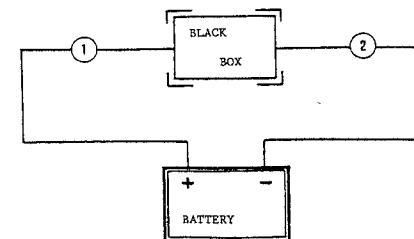


Figure 3: a question to test a "system view" of the electric circuit.

answer to one question and to generalize the consequences to each similar situation especially when similarity isn't bound to something concrete and local like a resistor or a bulb but to some abstract and global concept like the concept of circuit. Nevertheless if we adopt a description of the student's representations in terms of reasonings, it seems that the only way for a student to accept the correct answer to the questions with a resistor is to change his sequential reasoning. It's interesting to see if it is actually the case that he changes his mind how does he change.

#### A economical law.

To study the way students react to a cognitive conflict it's necessary to study not only the answers to questions we ask but chiefly the comments the students do.

A very primitive reaction is to refuse results. By instance about question 2 a student said: "Oh yes the resistance is not big enough bulb 2 to be dimmer". That's the reason we increased resistance and the student said: "I cannot understand, please explain!" Another student after the same first answer to question 2 said: "I can prove it". He built a circuit with a 470 ohm resistance and a bulb in serie. And he said: "Look: the resistor consume too much current and the bulb cannot shine." Another student's tendency is to modify their reasoning just enough to make it consistent with the only one experience they are busy with. By instance about question 2 a student said: "Current is just like water,

in the resistance it slows down and after it, it recovers the rate it has had before; so the two bulbs shine in the same way".

One could hope that manipulations can lead pupils to adopt a "close circuit" model or at least a "bipolar" model even if it is a "clashing currents" model (OSBORNE 1981). We tried to test that proposing this question (fig. 4) to 53 pupils in secondary school after elementary manipulations with electric circuits:

"Will the bulbs shine or not? Why?"  
85% of the pupils answered: "No, plus and minus need to be in contact."

This kind of comment let us think the cognitive conflict created by the failure of the well-known "monopolar" model could have very limited effects.

We tried to test that with the following question (fig. 5) asked to the same pupils: "We connect battery to the circuit. Which bulbs do shine? Do they shine always? Why?"  
Only 37% of the pupils gave the correct answer; 41% answered that 1, 2 and 3 light up and 22% that 1 shines and 2 and 3 wink. In this case pupils seem to be thinking that the

contact between plus and minus through bulb 1 is not a condition to make it shining but a condition to make the battery working. And if the battery works any bulb connected to the battery can shine. Thus it appears in this case that the "monopolar" model is not really modified. It is just improved by the condition of a contact between + and -.

#### Towards metacognition.

This relative failure of the cognitive conflict is not so astonishing. If we never say to the students the reason why we propose such disquieting experimentations, how can they think something else that the

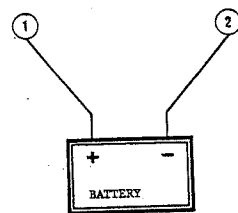


Figure 4: a question to test a "close circuit" model.

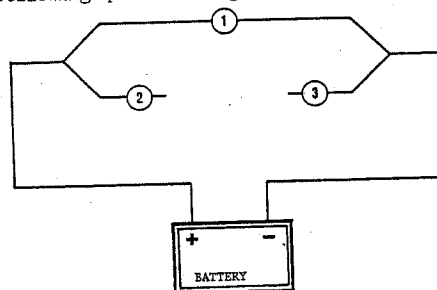


Figure 5: another question to test a "close circuit" model.

only important thing is to justify the answer - given by experimentation - to the only question we proposed, and of course, by the simplest way?

So, we think that it's necessary to make the students conscious of their own reasoning and to repeat experimentations or questions to introduce by teaching another reasoning. That's what we tried with our students. Before manipulations we proposed them a writing test about, by instance question 2 (two bulbs and a resistor in serie). After a few minutes, without taking the slides back and without looking on it, we gave the students their own answer and we explained their own reasoning better they could do. They were very astonished. Then we criticized their answer and we proposed another one with a correct reasoning. Manipulations could then be done by the students about the same kind of problem. We proposed then to the students a bet: next week, we said, we'll ask another question about the same problem and you'll make a similar mistake with the same reasoning you use first this time. Nobody wanted to take the bet but the following week for some of them we lost our wager. For the other ones we started again giving their answer, criticizing it and so on... After some weeks, nearly 100% of the students gave a correct answer with a correct reasoning about more and more unusual situations concerning the concept of circuit.

#### More than metacognition.

So doing we can hope the students learned a correct view of the circuit and are able to use in an appropriate way the physical concepts - per ex. potential difference - to describe it. But to obtain this result it's necessary to destroy, or to try to destroy, the student's natural reasoning. Moreover the price to pay for that is to put the students in a position of failure until they are able to use a "system view" of the circuit and to let them think that any other view is incorrect. But it isn't always useful to take into account interactions in the circuit to solve problems in electricity. It's especially necessary when something is modified in the circuit. But in some other cases one can also use simpler reasonings. By instance when we have just to build a circuit or to detect some breakdown in it, it's easier to follow the circuit just like with a sequential reasoning solving problems step by step. The problem of the feed-back is generally not relevant in this



case. To solve the first part of the question 2 it's no more necessary to use something else than a "constant current" model of the circuit. Is this model correct? Of course it is, because it works! Moreover this question of correctness of a model is meaningless: a model is useful or not useful and in this case a "constant current" model is useful as long as the resistance of the circuit isn't modified. But students usually don't take this condition into account. Thus if the students have to learn a "system model" of the electric circuit, it's not necessary, not useful and, as we showed ( CLOSSET 83a ), impossible to destroy the other "natural" models. But it's really important students to be conscious of limitations of such "models". To reach this aim we have to teach what a model is. In this context cognitive conflict will be useful, not to learn what is true and what isn't true but to fix limitations to each model. And that is actually a physical proceeding.

Teaching the concept of "model"

We used the term "model" as one can see, not really with the same meaning it can have in physics, namely it's not for this moment, a formal model and his coherence can be more limited. Similarly our suggestion of teaching what a "model" is deals with a similar meaning of the term "model". Nevertheless the concept of "model" could be considered to be a very abstract one. That's the reason why we would like to suggest first the use of very concrete analogies.

A mock-up of an object is not the object but can give a lot of information about this object. It's a concrete model of this object. A little more abstract model of an object is a map. Per example in the underground one can see maps of the railway lines. These maps can be only predictive of the sequence of the railway stations. It's not possible from such a map to know the distances between stations or the time one need to go from one station to another one. Nevertheless a underground map can be considered like an elementary and partial model of a town. But it's also possible to use more sophisticated models (maps) of the same town: it depends what you want to know. And it's always easier to use the more relevant map to your preoccupation which is not necessarily the more sophisticated one.

Similarly in physics we can use simple models of the electric circuit if we are only concerned by some elementary aspects of this

circuit. But we have then to know what those models can describe. In this respect some "natural" models of the students can be used in teaching if this teaching leads the students to be conscious of the limitations of such elementary models.

After using concrete models and maps, it's possible, we think, to introduce graphs like a way to build models of an experimental process. One have then to discute what can be predicted from those graphs and what confidence we can have in those predictions. Building of formal models from graphs would be the last step of this teaching of the concept of model.

This leads us to another important remark. Concepts we use in physics are formal concepts well adapted to be used in formal models. It's not evident that these concepts are adapted to an elementary approach of the electric circuit. We think it's necessary first to introduce more simple concepts better adapted to the description of elementary models of the electric circuit. But that's another subject.

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The Introduction of Voltage as an Independent Variable -  
the Importance of Preconceptions, Cognitive Conflict and  
Operating Rules

Christoph v. Rhöneck

1. Introduction

The manipulatory analysis of simple electric circuits, additional interviews, and the concept mapping of the semantic structures lead to converging descriptions of the students' preconceptions regarding electric phenomena. Tiberghien and Delacôte, 1976, emphasize a linear causal effect between batteries and bulbs, that means the battery acts on the bulb. Fredette and Lochhead, 1980, use a sink model to describe the students' conceptions. Andersson, 1980, points out the source-consumer model for electric circuits. Maichle, 1982, uses a give-schema to analyze the processes in a circuit. Finally, Rhöneck and Völker (v. this book) interpret the semantic structures on the basis of a so-called students' energy view where current and energy flow are intermixed. Common to all of these studies is a one-dimensional description of the processes in a circuit. The term 'one-dimensional' will become clear in the next section.

The outcomes of the research work on representation should improve the design of instruction. One component in search of better teaching methods could be to define such situations which are incompatible with the student's preconceptions. In this way conflicts may be produced between prospective learning materials and the student's preconceptions. These conflicts could be used to analyze the argumentation which usually hinders the development of a more adequate knowledge structure. As expected, the primitive conceptions tend to assimilate the incoming information. This may be illustrated when the student has been exposed to  $i = \text{const}$  (v. next section). The constraint  $i = \text{const}$  should be incompatible with the above-mentioned conceptions. But the conservation of current is accepted on condition that the students introduce a second variable. This second variable describes a property of the

electric current and is related to the student's idea of voltage.

The formation of an independent concept of voltage is a main objective in teaching basic electricity. Generally, the concept of voltage is not developed as an independent concept in a first period of instruction. Even more advanced students usually do not use the voltage concept when their problem-solving strategies are analyzed. For that reason special efforts are necessary for the development of the different aspects of a voltage concept.

## 2. The conflict between $i = \text{const}$ and the explanation of a used battery

In order to study a conflict between the student's pre-conceptions and the constraint  $i = \text{const}$  some students were interviewed. In total 15 students of grade 9 in a "Gymnasium" (grammar-school) participated. These interviews were carried out prior to a first period of instruction. The dialogue began with the questions how to make an empty electric torch without batteries work and what happens when the torch is switched on. This introductory discussion should show which terms were used spontaneously by the students. All students but one used the term current to describe the processes in the electric torch.

Then the student was asked to describe the current in a circuit with one bulb and two round cells in series (v. fig. 1). All students had already formed an idea of the current in the circuit. Primitive ideas with unidirectional currents and more sophisticated models with circulating currents were used. After the student predicted for example a current from the positive pole to the battery the current was measured with an ammeter. Afterwards the ammeter was used to demonstrate  $i = \text{const}$  subsequent to the predictions of the student what will happen in the second wire and between the two round cells.

During the interview the students were confronted with the conflict between their predictions and the reading of

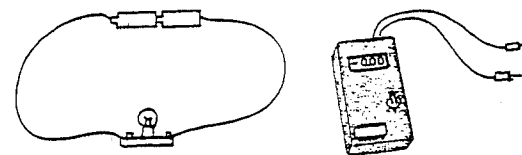


Fig. 1: The circuit used in the interview.

the ammeter. The difference between the students' concept of current and the current measured by the ammeter was part of this conflict. Since  $i = \text{const}$  was accepted the students were subsequently asked to answer the following question: When the current goes round and the current is unchanged what is meant by "the battery becomes unusable"?

In the following, some selected excerpts of the interviews are quoted. The first excerpt rather demonstrates a primitive picture.

Vi (Vi said that two currents meet in the bulb:)

I: Does a current flow in the battery?

S: No, the current is stored up in the battery.

I: (After demonstrating  $i = \text{const}$  in the battery:) Could you explain why even in the battery a current flows?

S: There are molecules or something else in there and I believe, that this ... (uncertain remark)

I: Is it possible that the current goes this way and the opposite way as well to the bulb after we have measured an unchanged current before, after, and in the battery?

S: Yes, that's possible.

I: How does it work?

S: Oh, I do not know, I have no idea.

I: The current does not flow this way. Has "electric circuit" ever been explained to you?

S: Yes, but I was never concerned with it.

I: Namely, that is to say the current flows in a circuit and flows through the battery. Please, could you answer

me some additional difficult questions? When the current goes round and the current is unchanged in all parts of the circuit what does it mean to you "the battery becomes unusable"?

S: Though the circuit is closed the current loses more and more its force. That happens a million times in the circuit.

I: Where does the current lose its force?

S: In the bulb, there it is consumed.

First of all, the student comes to a point where a second variable is introduced. This second variable appears as a property of the electric current in the paraphrase "force of the current". This force of the current often reappears in the circumscriptions of the student's concept of voltage before and after instruction.

In the next interview another solution becomes visible. In this case the student introduces a second variable, too.

Co (The student decided on clashing currents after the demonstration of  $i = \text{const}$  before and after the bulb:)

I: Does a current flow in the battery?

S: No, a current through the battery, that's impossible.

(After the demonstration of  $i = \text{const}$  in the battery the student laughs and says:) The old batteries are empty, therefore the current has to leave. Perhaps less current goes back or nothing comes back to the battery.

I: How does it work when the current is the same in the battery, before, and after the bulb?

S: Perhaps with the pressure, I really don't know.

I: And what happens when the battery is used up?

S: When the current is not so strong, perhaps the bulb shines less bright, perhaps the current was pressed in the battery. The current goes through the wire and afterwards the pressure decreases.

I: What means the battery is used up?

S: The battery has no more pressure and there is no more current in there, the current is used up.

I: Even though the total current flows back as we have seen?

S: Yes, but the energy ...!

The energy is used up. What I mean is: I am able to run and when I am exhausted the energy is lost.

When confronted with  $i = \text{const}$  the student uses the pressure produced in a battery as a second variable. In this picture the second variable is not a property of the electric current. At least the student does not use the word pressure in a minor function. This interview is remarkable for a second reason. The energetic aspect of the student's concept of current becomes evident in the last section of the interview, where the student explicitly equates current and energy.

In these two interviews the students did not spontaneously refer to circulating currents and circuits. In the following, the students make use of circulating currents. To begin with, an excerpt will be discussed where the student combines the circuit with the consumption of current.

Ge (Ge pointed out that the current flows in a circuit:)

I: Does a current also flow in the battery?

S: Yes, the current flows through the battery.

I: How much current flows in the battery?

S: As much as in the wires.

I: When the current goes round and the current is unchanged what is meant by "the battery becomes unusable"?

S: The current is consumed very slowly. The bulb would not shine when the current could not flow through the bulb.

In course of time so much current is consumed that it can not be delivered in the same way and the bulb shines with less brightness.

I: When the battery gets back the total current, why does the battery become empty?

S: In any case there is a loss. A minimal loss but it becomes apparent after some time. And the voltage decreases.

I: Now, you use the term voltage.

S: Voltage is the strength of the current. The voltage in a transmission line has more strength than the voltage in a battery. There is a difference between electrical devices which consume more or less.

I: What happens to the voltage when you go around the circuit?

S: Even the voltage stays the same.

This student combines  $i = \text{const}$  and the consumption of current. The student begins with the statement  $i = \text{const}$ . Only the hint at the unusable battery provokes the idea of a consumed current. Via a "minimal loss" the constraint  $i = \text{const}$  and the consumption come to be nearly compatible. In total three students out of 15 students searched for a compromise like this.

In the above-mentioned interview the student introduces the term voltage, too. Voltage as a second variable regulates the "strength" of the current. Beyond that the same rule "stays the same" applies to current and to voltage. Voltage and current are closely associated.

The next student already works with a circulating current and  $i = \text{const}$ .

U1 (U1 uses the electric circuit)

I: Does a current flow in the battery, too?

S: Yes, here are two batteries in series and the current flows from the last round cell into the first.

I: Is there a difference between the currents before and in the middle of the two cells?

S: No, the current remains the same.

(After demonstrating  $i = \text{const}$  between the two cells:)

I: When the current circulates and the current is unchanged what does it mean to you "the battery becomes unusable"?

S: The current flows from the positive pole to the bulb. There the current is transformed into light and afterwards the current must flow to some place, that is why the current flows back.

I: You say the current is transformed into light. Does that mean less current flows back? (No reaction.)

We have seen the same current flowing back. Therefore the battery never should become empty.

S: It is possible that after a while the current decreases from 0.09 to 0.06 and on this account the bulb becomes darker.

I: Can you explain why the battery becomes empty when the entire current flows back?

S: The current is worn out.

I: What does happen in the bulb?

S: The bulb consumes a little bit and the used current flows back.

I: How does it work?

S: In a transmission line the current is sent away with many volts. Less volts arrive at the plug. On the way the volts are lost. In this case it is the same.

When this student talks about a consumption of current the aspect of devaluation and not the aspect of diminution seems to dominate. In this way  $i = \text{const}$  becomes understandable and the devaluation of the current is associated with the volts which may be lost. The voltage is described explicitly as strength of the current.

The following interview shows that  $i = \text{const}$  may be accepted without restriction. The current is seen as constant around the circuit and the consumption of voltage describes the energetic aspect:

Ra (Ra uses the concept of circulating currents:)

I: Does a current flow in the battery?

S: Yes, the current is the same everywhere.

I: (After demonstrating  $i = \text{const}$  in the battery:) When the current circulates and the current does not change what does it mean to you "the battery becomes unusable"?

S: I mean the electrons are slowed down and then the current decreases. In the circuit are teeming electrons, the first electron knocks against the next electron and the electrons go round. Some time the electrons are not so fast and the bulb dims.

I: What is the reason for the slow-down of the electrons?

S: For example there is friction and some heat is given to the wire. When the current increases very much the wire becomes hot.

I: A little while ago (in the first part of the interview) you used a second term, voltage. Please tell me what is voltage?

S: Voltage means how many volts come from a battery or another source. In this case we have 3 volts. Before the bulb are 3 volts and after the bulb are zero volts because the voltage is consumed.

This student is acquainted with  $i = \text{const}$  and his description of the energy flow is compatible with the invariability of the electric current. His explanation of the energy flow is simple: The second variable, voltage, is used for this purpose.

The quoted excerpts of the interviews contain a changing and a static element. Obviously, a development from an unidirectional current to a circulating current is possible. The students accept the corresponding energetic questions. But the solution of the energetic problems reach only a certain level which represents a rather primitive picture: The student tends to introduce a second variable when confronted with  $i = \text{const}$  and when asked for an explanation of the used battery. This second variable frequently is defined and described as voltage, strength of the current, or force of the current. In this way before instruction the second variable and the concept of voltage are predetermined to a certain extent. Strictly speaking the primitive one-dimensional view is preserved. Hence it follows that special efforts will be necessary to come to a multi-dimensional description including an independent concept of voltage.

Conflicts alone are not sufficient for a change of the view. The student may solve the conflict with rather vague and broad students' concepts. The incoming information  $i = \text{const}$  may be assimilated to his preconceptions.

### 3. The introduction of voltage

The introduction of the concept of voltage in grade 8 or 9 is difficult for several reasons. First of all, the preconceptions of the student should be mentioned.

Secondly, the problem arises in which way the concept of voltage should be introduced. The students are acquainted neither with electric fields nor with the concept of potential difference. So a formally correct definition appears

to be impracticable.

Thirdly, the necessary circumscription of voltage should enable the student to predict voltages in simple problems and to handle a voltmeter. The preliminary circumscription of voltage should be improvable in later teaching sequences.

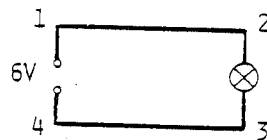
Some short remarks may be allowed on the circumscription of voltage. In many textbooks voltage is described as the drive of the electric current. This means that something is moving in the circuit, and this something does not move without a drive of a battery or another source. Besides this meaning the word "drive" has a considerable dynamic aspect. But voltage in physics is not a force, it is a potential difference.

The necessary revised information on voltage may be introduced in different ways. Sometimes voltage is described as the amount of energy given to a single electron per charge of the electron ( $V = W/q$ ). This energy is delivered to the electron in the battery and given to the lattice in the resistance. Such a definition results in difficulties when for example the energy transfer in more complicated circuits should be explained to the student. An alternative approach may be started with measuring the voltages across the battery, the wires, the switch, and the bulb in a circuit. These activities serve to break the strong connection between voltage and current. Following these measurements, the student may be able to find a rule on his own: A voltage is measured when the measurement device is connected with plus and minus. Provided that the teacher previously explained the poles of the battery with the lack and the surplus of electrons this rule may be improved: In a circuit a voltage is only measured when a charge difference exists. In this primitive model the battery is a device that constantly maintains a charge difference across the poles no matter what current flows. The charge difference stands for the abstract potential difference and "causes" the current in a circuit. It should be noted that charge differences are actually necessary in a circuit. They are found on the surface of the conductors and are pro-

ducing the electric field inside the wires that makes the electrons run (v. Walz in this book). When these effects are discussed during a later period of instruction the picture of charge differences on the surface may be extended.

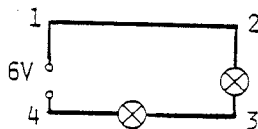
The circumscription of voltage as a charge difference enables the student to use simple operating rules when voltages are to be predicted. Across two bulbs connected in parallel the same voltage exists because the charge difference produced by the battery appears across either bulb. The voltages across two bulbs connected in series sum up to the voltage across the battery because the charge difference across the battery drops across both bulbs. A voltage is measured where a charge difference exists. The results with these operating rules are promising. The following example of a task has shown that 8th- and 9th-graders are able to use the rules correctly.

Look at the following circuit:



Insert the values of the voltage across the points  
1 and 2: \_\_\_\_ V, 2 and 3: \_\_\_\_ V, 3 and 4: \_\_\_\_ V

Now a second bulb of the same  
type is added:



Insert the values of the voltage across the points  
1 and 2: \_\_\_\_ V, 2 and 3: \_\_\_\_ V, 3 and 4: \_\_\_\_ V

Fig. 2: Voltages in a circuit

About 90 % of correct answers for part 1 and about 52 % for part 2 were achieved in different groups directly after instruction whereas students without experience with vol-

tages in a circuit generally could not solve part 1 of this task. In a smaller sample of 56 students the percentage of correct answers decreased to 70 % and 22 % four month after instruction.

Even more important is the fact that some students may use spontaneously the voltage concept 4 month after instruction when they were confronted with the problem of figure 1 and when exposed to the following question: When the current circulates and the current has the same value everywhere in the circuit what does it mean "the battery becomes unusable"? Here are some answers from students of the "Realschule" (technical school).

- In the battery a chemical reaction occurs and in this way a current is produced. When this reaction comes to an end no longer is a charge difference formed.

What was our expression for charge difference?

The unit was volt.

And what was the name of the term?

Voltage.

- The battery resembles two linked water vessels. When the two vessels are connected the water level equalizes. What corresponds to the level difference in the battery? The voltage.
- In the battery is a chemical liquid. The electrons which emerge from the negative pole accumulate there. They flow to the positive pole and back through the liquid. When the liquid comes to an end the voltage is zero.

It should be emphasized that the instruction of these students contained an explicit discussion of the different views of the processes in a circuit (energy view and  $V/i/R$ -view) and the detailed application of operating rules which describe the voltage concept.

These results should be seen in connection with our hypothesis that conceptions and views are an important cognitive component which constitute part of the student's understanding of basic electricity. The preconceptions seem to be rather resistant even to cognitive conflicts. The broad

and vague students' concepts allow a multitude of explanations within the students' primitive views. The development of the naive preconceptions to a simplified scientific theory could begin with a certain disequilibrium produced by cognitive conflicts. But essential additional information seems to be necessary to change the preconceptions of the student.

Do we know what is an essential additional information? Part of this information could be the bicycle chain model for  $i = \text{const}$ , comments on the distinction between current and energy, or the emphasis of an independent voltage concept. In this way a multi-dimensional description may be promoted which is necessary for an understanding of basic electricity and for problem-solving in this domain.

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#### TEACHING CHILDREN TO DISCRIMINATE BETWEEN CURRENT AND ENERGY

David M. Shipstone and Richard F. Gunstone

#### Introduction

Investigations have shown that many children interpret D.C. circuit phenomena in terms of a variety of conceptual models of a source-consumer type (e.g. Tiberghien and Delacôte, 1976; Osborne, 1981; Shipstone, 1984), some of which survive long periods of instruction. Osborne (1983) investigated the possibility of converting children to the scientists' view of current using cognitive conflict and found that all but five of the forty 8- to 12-year-old pupils involved were able to see that that was the only model supported by the experimental evidence. There was no suggestion, though, that the children's ideas had been permanently changed by this rather isolated experience. The same conflict procedure was subsequently incorporated into a course of instruction (Cosgrove et al., 1983) after a period of familiarisation with simple circuits and before work on a range of practical problems. In one class of thirty 14- to 15-year-old girls, above average in ability, about 50% identified the correct model six weeks after the course but 40% of those who had selected this view immediately after the conflict experience now rejected it. These authors identified the central problem as the pupils' inability to separate their ideas on current from the notion of energy. The study described here was principally aimed at training children to discriminate between these concepts.

#### The training programme: development and implementation.

The starting point in the development of the teaching materials was that the source-consumer view of electricity with which most children approach their studies approximates much more closely the scientists' notion of electrical energy than it does their concept of electric current. Lack of precision in children's use of terminology also plays a very significant role in reducing the efficiency of communication between themselves and their teachers. So the first object-



ive was to provide the pupils with the accepted name, electrical energy, for their embryonic concept and introduce the term current later, in the hope that this would help to clarify the distinction between these quantities. The procedure thus followed the well tried pedagogical principle of 'starting from where the children are in their understanding and leading them from there to where we want them to be', as advocated in this context by Hirtel (1982).

Following 2-3 lesson trials in Australia the approach was incorporated into an existing secondary school course for 12- to 13-year-olds in Britain. At this point it was felt more appropriate to adapt the course in other respects as well, in the light of the available evidence about children's learning difficulties in this subject. The mixed comprehensive school used for the experiment serves part of a large housing estate, owned by the local authority, on the outskirts of Nottingham. At age 11 the average reading age of the intake is approximately 6 months below the national average. Two mixed ability classes, taught by the same experienced teacher (a biologist), formed the experimental and control groups with 25 and 24 pupils respectively. Except where stated otherwise both groups followed identical programmes.

The course involved pupil experiments with circuit boards and Test 1, the pre-test, was administered as soon as they had had their first experience of setting up a circuit with one battery and one bulb, referred to hereafter as 'the simple circuit'. The pre-test had three components:

- A 9-item matrix of diagrams of unmounted MES lamps connected variously to a cylindrical cell, the task in each case being to say whether the lamp would light or not. (cf. Andersson and Karrqvist, 1979).
- Four questions asking pupils to explain in their own words the action of the battery and the lamp and what happens in each of the connecting wires in the simple circuit.
- A multiple choice question about the simple circuit to discover the children's models for 'electricity'. This

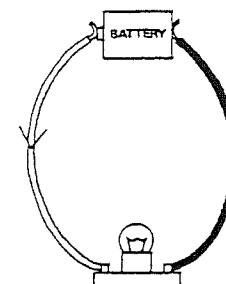
was the term selected for the pre-test as that most commonly used by the pupils themselves. In later tests this 'models test' took the form outlined in Fig.1.

A question about electric current and electrical energy.

The diagram below shows a battery connected to a lamp. The arrow on the WHITE wire shows which way the current in that wire is flowing. What do you think is happening in the BLACK wire?

- In the BLACK wire, is there
  - an electric current flowing towards the lamp
  - an electric current flowing away from the lamp
  - no electric current at all?

Answer a, b or c ☐



- Compare the black wire with the white wire.

Does the BLACK wire carry

- more electric current
- the same amount of electric current
- no electric current at all
- some electric current, but less than the white wire?

Answer a, b, c or d ☐

- Does the BLACK wire carry

- more electrical energy
- the same amount of electrical energy
- no electrical energy at all\*
- some electrical energy, but less than the white wire?\*

Answer a, b, c or d ☐

(\* Answers accepted as correct)

Fig.1. The 'models test'

The pre-test results are shown in Fig.2, together with those of the other tests given throughout the course. The percentages conserving current and discriminating between this and energy are given for those 18 pupils in each group who sat both the pre- and post-tests and had few absences.

The course continued with an investigation of the requirements for a complete circuit using a lamp to indicate

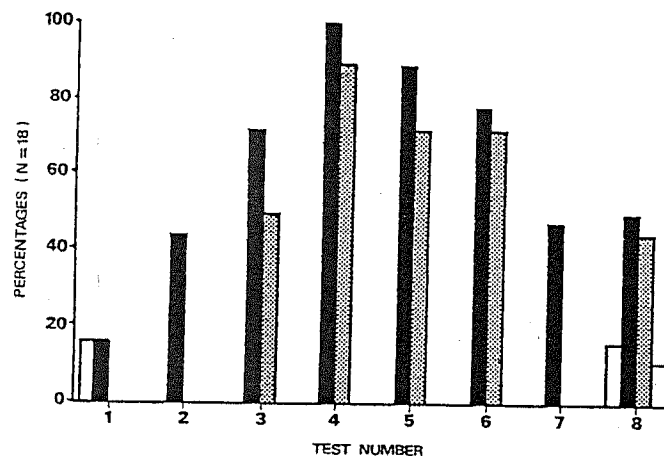


Fig.2. Percentages of pupils in the experimental group with the accepted model for current  and discriminating between current and energy  Corresponding evidence for the control group.

continuity. The identification of conductors and insulators came next, followed by examination of the MES circuit board lamp to emphasise its two contacts and the conductor running right through it.

Up to this point both groups had followed the same programme but here the experimental group was introduced to the term 'electrical energy' as the name to be used for what it is that the battery supplies and the lamp 'uses up'. These pupils then used this term to interpret their observations of a range of series and parallel circuits.

The electric current was introduced to the experimental group through its magnetic effect and some information about current directions was acquired by investigating the field around the wires either side of a lighted lamp with plotting compasses. Following introduction of the ammeter, Test 2, the full 'models test', was used to expose the children's ideas on current and on energy transfer, after which their beliefs were challenged in the manner described by Osborne (1983). A centre-zero demonstration ammeter was used to

measure the current on one side of the lamp in the simple circuit and they were asked to predict, for each model, the reading it would show when moved to the other side. The implications of the subsequent measurement for the validity of each of their models were then considered. That 44% supported the accepted model for current before the conflict procedure was used is difficult to understand: possibly it had been mistakenly assumed that the experiment with plotting compasses indicated 'same size' current as well as 'same direction'. Nevertheless, Test 3, the models test again, showed that after the conflict experience a much higher proportion, 72%, supported the accepted view and 50% discriminated correctly between current and energy. Class experiments followed in which the current was measured at various points around a series circuit.

These experiences raised the question of what the current does since it clearly is not consumed within the circuit elements. To explain the current's role as a transporter of electrical energy children in the experimental group were asked to consider the similar behaviour of the circuit and the simplified hot water central heating system shown in Fig.3, an approach suggested by Härtel (1982). The explanation given was that the current consists of a flow of

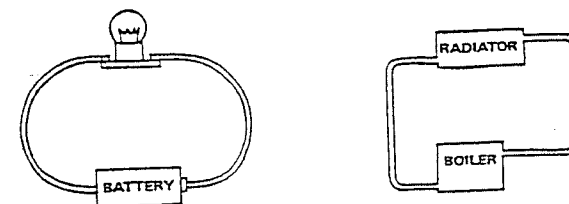


Fig.3. Simple circuit and heating system analogue.

electric charges through the circuit: that these charges gain electrical energy in passing through the battery and carry this energy to the lamp: once there they give up their electrical energy, which is used to produce heat and light, and return to the battery where the cycle recommen-

ces. This approach, which does some injustice to physics, was adopted in the interests of providing these young pupils with a simple picture which would be sufficient for their immediate needs.

Both as a test of understanding and to exploit cognitive conflict again a working circuit was set up with a battery and two dissimilar lamps. Qualitative questions were asked about the relative quantities of energy used in the two lamps and the current in each. On this, Test 4, the pupils performed very well, all of them applying the scientific model for current and 89% discriminating between current and energy. The current in each of the connecting wires was measured with a centre-zero ammeter to reinforce the correct model and challenge what few others remained. The procedure was repeated using two identical lamps in series, Test 5, in which case it was necessary to ask about the relative amounts of electrical energy transported along the different connecting wires. The models test given at this stage, Test 6, revealed that 78% preferred the scientific view with 72% distinguishing correctly between energy and current.

With the introduction of resistors as distinct elements in circuits came the possibility that the children would begin to develop a sequence model for current (e.g. Shipstone, 1984) and an attempt was made to forestall this. Pupils were shown the circuit of Fig.4 and asked to predict

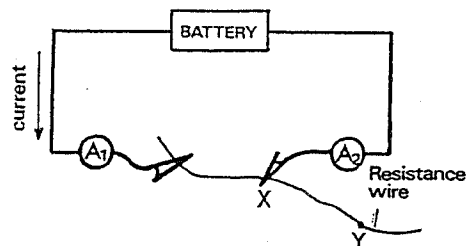


Fig.4. Circuit employed to expose use of the sequence model.

the effects upon the ammeters of sliding the crocodile clip at X along the wire to Y. In this, Test 7, which gave no evidence about discrimination, 47% of the group conserved

current and the attempt to combat the development of the sequence model in the experimental group by cognitive conflict was abortive because none of these pupils had applied it. Nevertheless an explanation was given, using an analogy, of how information about changes comes to be transmitted in both directions around a circuit.

More consideration was then given to series and parallel circuits, with current measurements made around the latter. The course ended with experiments on the heating effect and fusing, by which time both groups had had about 22 lessons, each of 1 hour's duration.

#### Post-test results and discussion.

The remote post-test, Test 8, was given 3 months later in separate sections as follows:

- a) As (a) in the pre-test.
- b) As (b) in the pre-test plus six items, mostly qualitative, testing for conservation of current.
- c) The models test plus a question about two dissimilar immersion heaters, connected in series and producing different temperature rises in equal volumes of water, which was used as a check of discrimination between current and energy.

The performances of both groups on part (a) were just slightly worse at post-test than at pre-test. By the time of the pre-test, immediately after the children had set up their first circuit, around 75% had already appreciated that both ends of a cylindrical battery must be connected to a lamp, a performance far better than that expected of true novices. Those items requiring an awareness that there are two separate contacts on the lamp, however, were only answered correctly by 50%, at best, in the post-test, showing that the construction of the lamp had continued to cause confusion.

It is convenient to discuss Test 8(c) next. The first item showed, pleasingly, that 50% of the experimental group recalled, at least, the accepted model for current only and 44% discriminated between current and energy, with large

differences between the two groups (see Fig.2). Further evidence of discrimination learning was obtained in interviews with two-thirds of the experimental group after the post-test.

By contrast, the answers of both groups in Test 8(b) were disappointing. Just what had been learnt and by whom is shown in Table 1. In columns (3) and (4) of this table the results from the pupils in the experimental group have been partitioned according to the current model used: a similar procedure was not worthwhile for the control group because

Table 1. Percentages of pupils succeeding on each element of post-test(b).

| Material learned                                                    | Control Group | Experimental Group |                  |              |
|---------------------------------------------------------------------|---------------|--------------------|------------------|--------------|
|                                                                     |               | Whole group        | Scientific model | Other models |
| Q1 Relationship between current and energy.                         | 14            | 20                 | 50               | 0            |
| Q2 Ammeter readings either side of a circuit element are identical. | 32            | 30                 | 50               | 17           |
| Q3 There is no current anywhere in an open circuit.                 | 5             | 15                 | 38               | 0            |
| Q4 Current is conserved in a parallel circuit. (Quantitative)       | 18            | 5                  | 13               | 0            |
| Q5 Resistance wire doesn't 'use up' current.                        | 14            | 20                 | 25               | 17           |
| Q6 The effect of a resistor is independent of its position.         | 5             | 15                 | 25               | 8            |
| Q7 Current is conserved through a series of identical cells.        | 27            | 40                 | 50               | 33           |
| <u>Sample sizes</u>                                                 | 22            | 20                 | 8                | 12           |

of the small number subscribing to the scientific model. The responses to two questions, in particular, deserve comment. Firstly Q.1, the free response question, yielded evidence of how pupils' use of terminology had changed as a result of

the course and this evidence is set out in Table 2. In view of the emphasis placed on terminology at the beginning of the course the very slight increase in the use of 'energy' within the experimental group is at first surprising. At post-test, though, it was usually used correctly, rather than superficially as in the pre-test. The increases in correct use of both 'current' and 'energy' were similar, though not as large as had been hoped.

Table 2. Acquisition of terminology

| Term employed | Experimental Group % |           | Control Group % |           |
|---------------|----------------------|-----------|-----------------|-----------|
|               | Pre-test             | Post-test | Pre-test        | Post-test |
| Electricity   | 72                   | 61        | 72              | 83        |
| Current       | 0                    | 39        | 11              | 33        |
| Energy        | 22                   | 33        | 17              | 17        |

Secondly the experimental group's poor performance on Q.2 is remarkable. This gave the reading on a centre-zero ammeter on one side of a lamp and asked for the reading on another to the opposite side, partly testing recall of observations made during training. The conclusion of 17% that the second meter would register zero seemed to result from confusion over what it was measuring, its description as a current meter in the question being of no assistance to pupils who did not distinguish between current and energy. Interestingly, the interviews revealed that the prediction of equal and opposite deflections, by 17% again, sometimes resulted from an appeal to symmetry rather than from belief in a clashing currents model (Osborne, 1981). Generally the responses revealed the extent to which previous experience is reconstructed in the light of prevailing beliefs rather than recalled faithfully.

The entries in columns (1) and (2) of Table 1 show that the experimental group outperformed the control group in most cases but the success rates were all low and the differences not statistically significant. Comparison of columns (3) and (4) shows that, within the experimental group, the

best performances on all questions came from those who supported the 'accepted' model for current and energy. Except for Qs.1 and 3 (where  $p < 0.05$ ) none of the differences was statistically significant, however. The low percentages in column (3) and the fact that no pupil was correct in more than three questions, together indicate that the 'successful' pupils possessed only some superficial knowledge and lacked an appropriate schema which they could call upon in a wide range of circumstances.

The proportion of pupils showing long-term retention of learning in Test 8(c) was similar to that reported by Cosgrove et al.(1983). Two conclusions are possible from the results of Test 8(b). The pessimistic conclusion is that the learning was not meaningful and of no value. The interviews, however, showed that the pupils lacked confidence in applying what they knew; when reminded of the difference between current and energy many who knew of this performed better on the questions. This leads to the more optimistic conclusion that if pupils are given wider experience of applying their knowledge then a course of this nature may yet yield very real benefits.

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## ANALOGIES FOR THE ELECTRIC CIRCUIT?

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## 1. Introduction

In learning situations, analogies, metaphors and models are very often employed in order to illustrate complex processes or systems. In teaching electricity, water analogies for current flow are frequently used. These water analogies appear to have a long tradition, which originated in 18th century models of electricity (see e.g. GÖTZ, 1898,190).

In the past twenty years, water models have been developed specifically for the teaching of the electric circuit in order to promote students' understanding in this area. Research into the models' effect on students' comprehension of electricity has also been carried out. The purpose of my paper is to examine both the models and the corresponding research work. The study is based on a theoretical framework, which will be developed in the following section.

## 2. Analogies and analogous models in physics teaching

### 2.1. Remarks on the concepts "analogy" and "model"

The concepts "analogy" and "model" are used with various meanings (for an overview see LEATHERDALE, 1974). Therefore it is necessary to begin by outlining the meaning of these concepts. Fig. 1 portrays the theoretical framework underlying my subsequent considerations.

- (1) Where teaching and learning processes are concerned, the concept of model M is embedded in a more general context, comprising relations between the object O, the learning subject S and the model M. The relations between the object O and the model M are called analogies.

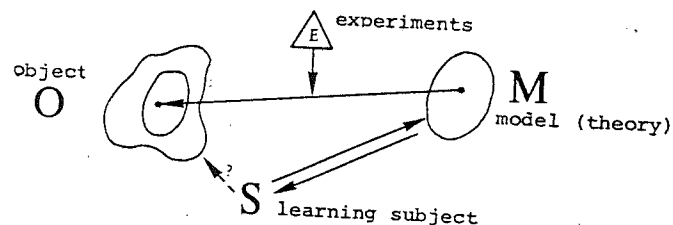


Fig. 1: The learning subject S can recognize the object O only with help of the model M and adequate experiments E.

When a subject S raises questions concerning the object O, they cannot be answered without the help of a model M. Model M has to correspond to conceptions of the subject S, while the relations between the model M and the object O have to be confirmed by experiments E.

- (2) In order to facilitate an understanding of the theoretical framework as outlined in fig.1, it is necessary to indicate the philosophical background. What is a physical object? What is an analogy? What is the role of experiments? What is the role of model and analogy in science and in science teaching? In the following two philosophical views are differentiated, which are outlined with a few remarks:

In the pragmatic view, i.e. an agnostic view of the world, model and object would be interchangeable, because all recognitions concerning the entities of the world would be "models". There would be nothing in the world that is not a model (STACHOWIAK, 1973). In the realistic view, the world is divided into real objects and theoretical models. Data, coming e.g. from experiments, are traces of reality. In critical realism as described by BUNGE (1973 b), the relations within the model M (e.g. physical laws) are in principle hypothetical. To state this fact, BUNGE (1973 a) calls the relations between M and O "analogous" as far as science is concerned.

He describes analogies in mathematical terms to be homomorphic, that means the relations between M and O are reflexive and symmetrical but neither transitive nor intransitive (BUNGE, 1973 a). The missing transitivity is responsible for some problems in using analogies in physics teaching which will be discussed below.

### 2.2. Analogous objects, analogous models, analogous experiments

The term analogy is not only employed for the relations between M and O as outlined in fig. 1 but usually for "things" (LEATHERDALE, 1974), that means analogous objects which are used in science or in science teaching.

In the theoretical framework sketched in section 2.1. the use of such an "analogy" can be portrayed in the following way.

- 1 LUDWIG (1978) describes the realistic point of view in a different way from that outlined here, employing a more complicated mathematical theory. Of course, the philosophical problems of realism cannot be solved by mathematical theories. They can rather describe some features of these philosophical theories in an unequivocal way.

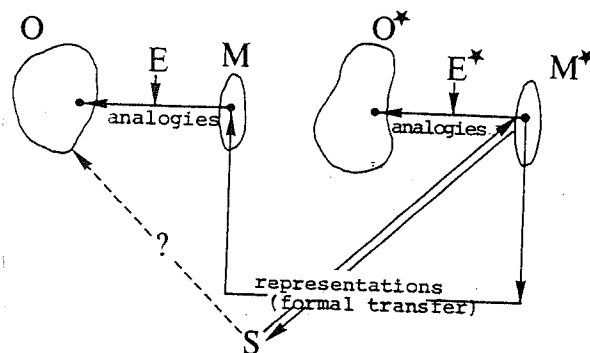


Fig. 2: Attributes of the object  $O^*$  and relations within the model  $M^*$  are transferred to the primary learning object  $O$  with respect to the model  $M$ .

The model  $M^*$  and the object  $O^*$  are employed to facilitate an understanding of the primary model  $M$  and hence of the primary object  $O$ . The concepts of  $M^*$  are defined as representations of concepts of  $M$ . "Pressure" for instance represents "voltage", or "water current" represents "electric current", where the "water analogy" of the electric circuit is concerned. Such representations (Symbol:  $\Rightarrow$ ) are isomorphic, i.e. they are transitive. Unfortunately, even if a formal transfer from  $M^*$  to  $M$  can be made, no advantage is gained for understanding  $M$ . We cannot transfer the physical laws from  $M^*$  to  $M$  without consideration of  $O$  and  $E$ . In my description the reason for this fact is the homomorphic relation between  $O^*$  and  $M^*$  and just the same between  $M$  and  $O$ . Because we have no isomorphic connection relating  $O^*$  and  $M^*$  to  $O$  and  $M$  we must learn  $O$  and  $M$  separately and independent of  $O^*$  and  $M^*$ .<sup>1</sup> But in this case the use of  $O^*$  and  $M^*$  in physics teaching would be absurd. This remark, of course, does not deny that there are numerous examples in the history of science where individuals had bright ideas sometimes caused by

<sup>1</sup> In this context I would like to mention that the worth of analogies is overrated. There were hot-tempered discussions between famous British and French physicists about 1900, and even today philosophers of science do not agree in the domain of analogies. For instance HESSE (1963, 119ff) gives mathematical proof that analogies for a scientific problem lead to higher statistical probabilities of being valid than other hypothesis. In the view of critical realism this is fundamentally false.

analogies. But the failures with analogies are not reported. So in short I would like to sum up: the rate of success with analogies cannot be computed. Only for the reason that learning situations are different from research situations can we hope that analogies can be fruitfully used in science teaching in an acceptable way. One difference between science and science teaching is that the results are known in the latter case; in science teaching there are no really unknown problems. Therefore in principle we can construct well corresponding analogies. This requires three guidelines (KIRCHER, 1981):

- (1) The analogous object  $O^*$  must be more familiar to the subject  $S$  and easier to handle than the primary learning object  $O$ . In addition, there should be some similarities in a "gestalt" aspect. For instance, the shape and perhaps the size of  $O^*$  and  $O$  should not differ too much from each other.
- (2) The structures of the models  $M^*$  and  $M$  (e.g. the physical laws) must be isomorphic in essential areas.

If there is an isomorphism between some parts of the structures of  $M$  and  $M^*$ , representations ( $\Rightarrow$ ) of some features of  $M$  in  $M^*$  and vice versa can be given. With this assumption an analogy could be useful for science teaching, because now for instance the corresponding physical laws must be learnt only within  $O^*$ ,  $M^*$ ,  $E^*$ , and in a second step we transfer the physical laws in a formal way to  $O$ ,  $M$ ,  $E$ . Usually there is no isomorphism for the whole structure of  $M$  and  $M^*$ , but only for certain areas. As far as the theories of the electric circuit and the water circuit are concerned, there are areas in which there is an isomorphism between the structures of  $M$  and  $M^*$ , for instance KIRCHHOFF's laws and OHM's law. But there are also areas where the isomorphism does not hold.

- (3) The experiments  $E$  and the analogous ones  $E^*$  must also be given attention. Usually the experiments  $E^*$  and  $E$  will be different, because there are only surface similarities between  $O^*$  and  $O$ . Of course, the analogous experiments  $E^*$  should be easier than the experiments  $E$ . But they also should be relevant to the students. As regards the electric circuit, experiments with the primary object, namely the electric circuit, are much more relevant than experiments with water analogies. This is true, for instance, with regard to the objective of teaching students' ability to handle electric devices in daily life. Whether experiments with the water circuit are easier than those of the electric circuit depends on the specific properties of the



water circuit employed. But usually experiments with the water circuit do not appear to be easier. I refer to this in more details in section 3.

### 3. An overview of water models<sup>1</sup> and empirical studies

As mentioned above, several water models have been developed in the past twenty years. Some of them will be presented in the following.

#### 3.1. The Nuffield water model

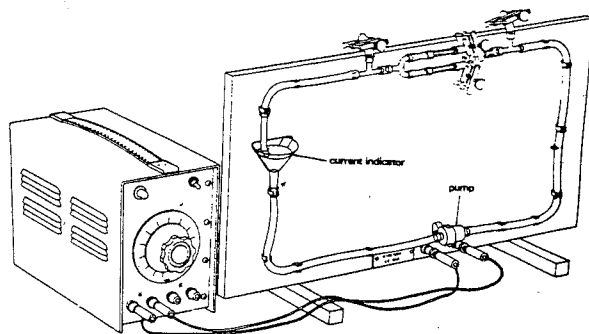


Fig. 3: The Nuffield water model (Nuffield-Physics, 1966).

WILKINSON (1972) carried out some research into the use of the Nuffield water model as portrayed in fig. 3. (33 students were interviewed after the model had been used in physics teaching). WILKINSON distinguishes four "types" in students' understanding of the water analogy.

Students of Type A (6 out of 33) think that in the tube the flow of water is constant for all points of the tube. They claim this even if the tube is squeezed in one point.

<sup>1</sup> In this section, the term "water model" is used for a "water circuit" used for teaching electricity.

Type B students (7 out of 33) think that the velocity of the water is constant even in the narrower parts of the tube. Though the students do not recognize any relation between water and electricity, they argue that the electric current has the same velocity at any point of the circuit, as they did in the case of the water model.

Type C students (11 out of 33) do not see any similarity between water circuit and electric circuit, the two circuits belong to different areas of reality. One student formulates this as follows: "We can see the water moving in the tube but we don't know what electricity does". I call the difficulties of these type C students the ontological problem: the students have severe difficulties in understanding the different ontological status of the object O and the analogous object O\*. This problem appears to arise especially in the initial stages of model use in physics teaching, when the students are not yet used to thinking within the framework of a model.

Type D students (5 out of 33) realize that the water current is constant, but they think that the electric current is not constant because electricity is compressible.

In my opinion, WILKINSON's findings point out that the Nuffield water model does not aid very much an understanding of the electric circuit to any great extent.

#### 3.2. The IPN water models

As part of an instruction unit on models of the electric circuit (IPN Curriculum Physik, 1975), I developed the water models presented in fig. 4. Some empirical studies investigating effects of these models as well as a specific electron model have been carried out. Approximately 800 students of grades 8, 9 and 10 (i.e. approximately 13 to 16 years old) took part in these studies. Only two hypotheses which are supported by the findings will be mentioned here.

(1) The above mentioned ontological problem became evident in many answers given by the students. Especially younger students and students of low ability in formal reasoning had difficulties with the different ontological status of the models and the electric circuit.

Fig. 4: The IPN water models

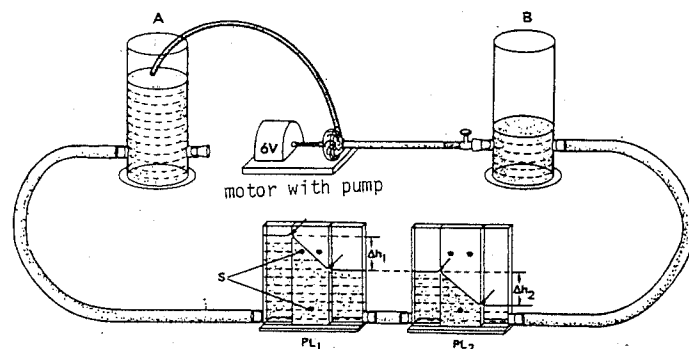


Fig. 4a: Watermodel with resistors  $PL_1$  and  $PL_2$  which are variable by screws  $S$ .  $\Delta h_1$ ,  $\Delta h_2$  represent voltage drops  $U_1$  and  $U_2$  in a corresponding electric circuit.

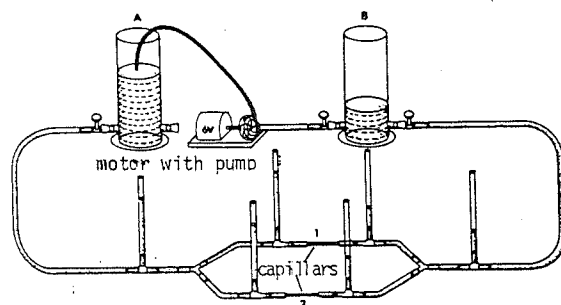


Fig. 4b: The vertical glass tubes indicate the water level before and after the capillars 1,2.

(2) Compared to a specific electron model, the water models (see fig. 4) appear better suited when introducing the concept of "current", whereas the electron model used in the instruction unit seems to be more appropriate when introducing the concept of "voltage" (KIRCHER, DUIT, 1975, 40). The findings indicate that this hypothesis is not valid in general, but only for the models used in the studies.

### 3.3. The Bremen water model

As outlined in more detail in another paper of these proceedings, H. SCHWEDES and her colleagues teach the water model for about 12 hours before teaching the electric circuit (SCHWEDES, SCHILLING, 1983). They argue that most students are familiar with a water analogy from every day experiences. They think that the water model is best suited for developing the idea of physical continuity, which is lacking among students' preconceptions in this area. I am not sure that this is indeed the true situation. The empirical studies carried out so far point out only that many students had a flow conception of current. That does not necessarily indicate that they have a water flow conception. Furthermore too much time may be invested in the water model, which is not of primary interest in physics instruction.

### 3.4. Water model and "teeming crowd model"

GENTNER & GENTNER (1982) investigated whether analogies are an important determinant of the way human beings think about a domain or whether analogies are used only as surface terminology when describing concepts in that domain. They compared the effect of two models of the domain. They compared the effect of a water model and a "teeming crowd model". GENTNER & GENTNER conclude that analogies are generative for scientific domains. Another set of findings throws some light on the use of water models. The water models aid not generally prove more fruitful than the "teeming crowd model". Some problems in the domain of the electric circuit are solved more effectively with the aid of a teeming crowd model than with the help of a water model (more details see: Y. J. TENNEY in these proceedings).

#### 4. Some consequences for using water models

Some considerations based on the "guidelines" for using analogies (see 2.2.) and on the empirical findings on the use of water models summarized in section 3, will be briefly listed in the following.

- (1) When using analogies (i.e. analogous objects and analogous models) it must be considered,
- whether the objects  $O$  and  $O^*$  are similar with regard to the gestalt
  - whether the theoretical structures of  $M$  and  $M^*$  are isomorphic in some relevant domains
  - whether the experiments in  $E^*$  are easier than those in  $E$  and whether they are relevant.

Furthermore it is necessary to be aware of learning difficulties.

- young and less intelligent students have particular difficulties in comprehending formal operations. Hence, they tend to mix up qualities of  $O$  and  $O^*$ .
- An ontological problem exists. Therefore, analogies may have no sense for some students.
- Water models are not easy to understand. Learning about a water model is probably as complicated as learning about the electric circuit.

General practice in "model thinking", including e.g. the range and the limitations of the model employed, appears to be of considerable help in overcoming some of the above-mentioned learning difficulties.

(2) There are several water models that have been developed in the past twenty years. With the help of these models relevant features of the electric circuit can be represented. The Bremen water model is easy to handle even for young students (say of age 10 to 12). But it is important to keep in mind that usually the very purpose of teaching the models is not the understanding of these models but the understanding of the electric circuit.

(3) Empirical studies so far have not been able to enlighten in a definite way the benefits of analogies for understanding physics. This is also true for the benefits of the water analogies. Therefore further empirical research is necessary. This research should not concentrate on finding the "best" analogy for the electric circuit. Instead different types of analogies should be developed and evaluated, which are appropriate to the different preconceptions of the individuals in a class-room.

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What makes analogies accessible:  
Experiments on the water-flow analogy for electricity

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Dedre Gentner  
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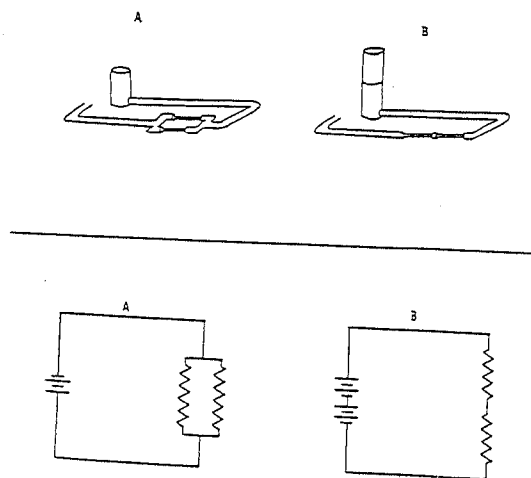
One of the most powerful ways to understand a physical system is by analogy. Analogies play at least two distinct roles in people's understanding of the physical universe. First, they are frequently used to explain new topics to students. An understanding of this aspect of analogy requires a theory of how analogies are interpreted or used. Gentner's (1983) structure mapping theory, for example, is concerned with the implicit rules by which people make inferences from analogies. Second, learners' naive mental models are often formed around their own self-generated analogies. For example, Gentner and Gentner (1983) showed that subjects' errors on a test of electric circuitry depended upon the particular spontaneous analogy they were using. The present study addresses the second issue, that of generative processes. How are analogies spontaneously generated?

A striking theme in the literature on problem solving (Gick & Holyoak, 1983) is that subjects do not readily notice that a solution that they have encountered in one context can be applied in a second, analogous context. A similar lack of transfer to problems that differ from textbook examples has been noted in discussions about the teaching of science (Duit, 1981). The present study examines possible ways of fostering analogical transfer using problems that resemble those students might encounter in a physics course. Our intuition was that problem solvers would notice that a second problem (the target) was analogous to a previously solved problem (the base) the more familiar they were with the domain of the first problem. This familiarity hypothesis was tested using the water analogy for electricity. In previous work, we found that subjects spontaneously drew upon their knowledge of waterflow in answering questions about electrical circuits (Gentner & Gentner, 1983). Although subjects did have misconceptions about water systems, they generally knew more about water than they did about corresponding problems in electricity. Others have shown that electricity is a particularly difficult subject area for students. Misconceptions about electricity tend to persist, even after instruction (Fredette & Lockhead, 1980; Rhoneck, 1984; Riley, 1981; Steinberg, 1983).

In two experiments, we examined the accessibility of the water analogy for electricity for subjects who knew little about electricity. Two analogous

tests were constructed, one in the domain of waterflow and one in the domain of electricity. In a series of problems, subjects had to compare the flow rate in two simultaneously presented electrical circuits (water systems) consisting of batteries (reservoirs) and resistors (constricted pipes). In both tests, the components occurred either singly or in serial or parallel pairs (see Table 1).

Table 1  
SAMPLE PROBLEMS



Experiment 1

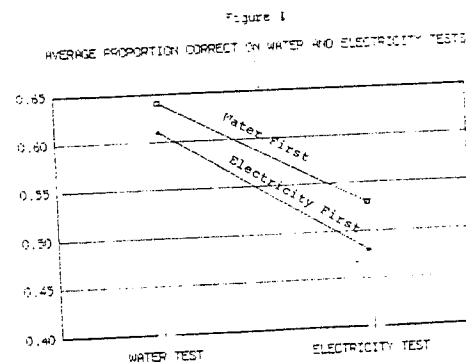
In this experiment the effect of prior familiarity on analogical transfer was investigated by varying the order of the domain tests. Half the subjects were given the water test first followed by the analogous electricity test, while the other half received the two tests in the reverse order. If familiarity is an important determinant of accessibility then subjects should show more transfer from water to electricity than vice versa.

Forty-eight undergraduates who had not had any college physics participated in the study. They were randomly assigned to either the water-first or electricity-first condition.

The assumption that novices intuitively know more about properties of waterflow than they do about electricity proved to be correct. Scores on the waterflow test, across conditions, were more than ten percentage points higher than scores on the electricity test, (62% vs. 51%), even though the problems on the two tests were strictly analogous. Furthermore, subjects spent significantly less time on each of the electricity problems than on comparable water problems (3.3 vs 4.1 seconds, respectively), suggesting that they were making more guesses and fewer calculations in electricity.

The question of interest, however, was whether subjects would transfer their knowledge about waterflow to the less familiar domain of electricity. In order to answer this question, we looked at the number of responses that were carried over from the last trial of the water test to the first trial of the electricity test and vice versa. The prediction was that there would be greater carryover of responses (whether correct or incorrect) from water to electricity than the reverse, because of subjects' greater familiarity with the water domain. This prediction was not confirmed. Although slightly more responses were carried over from water to electricity than from electricity to water (65% vs. 60%) this difference was not significant. These results suggest that subjects on the whole did not attempt to solve the unfamiliar electricity problems by analogy to the water problems.

Further confirmation of this lack of difference came from an analysis of electricity scores in the two groups. As can be seen in Figure 1, the water-first group had a slight but nonsignificant, overall advantage (possibly due to sampling). However, scores on the electricity test, relative to the water test, were not significantly higher for the water-first group than for the electricity first group, (i.e., the slopes were the same), suggesting that subjects did not transfer what they knew about water to the electricity problems.



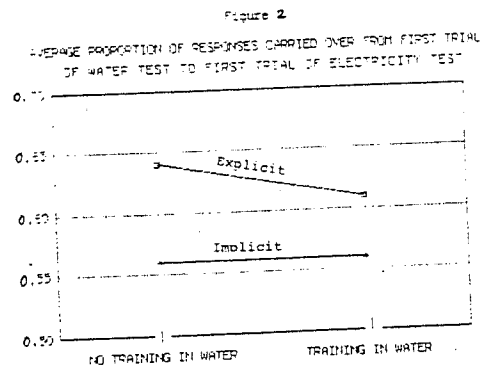
Further analyses were carried out in the water first condition to see if the water-flow analogy was beneficial for those subjects who did use it. Subjects were considered to have noticed the water-flow analogy if they showed a high degree of carryover from the water to the electricity test. Using carryover to predict performance on the electricity test, we found that the greater the carryover from water to electricity, the higher the electricity scores for this group ( $R = .56$ ). By contrast, the correlation between carryover from electricity to waterflow and performance on the water test was not significant for the electricity-first group ( $R = -.33$ ).

#### Experiment 2

The first experiment showed, contrary to expectation, that analogical transfer did not vary with the familiarity of the base domain. Although the water domain was more familiar than the electricity domain, subjects' understanding of water was still limited. Therefore, a second experiment was conducted in which familiarity with waterflow was induced through training. In this experiment, all subjects received the water test first followed by the electricity test. Half the subjects (the training groups) received feedback on the water test (i.e., the correct answers were provided) while the other half (the no training groups) received no feedback. Furthermore, half the subjects (the explicit groups) in the experiment were given explicit instructions to use the analogy to help them with the electricity test, while the other half (the implicit groups) received no mention of the analogy. Eighty college students who had not had any college physics participated in the study. The results of the experiment were similar to those of Experiment 1 in showing no effect of familiarity on the accessibility of the analogy.

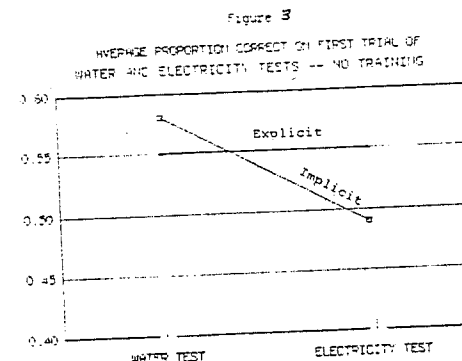
#### Analogy detection

The degree of carryover between tests, or the proportion of questions that received analogous responses, is shown in Fig. 2. It is clear from the graph that training in the water domain did not increase the degree of carryover of responses from the last trial of the water test to the first trial of the electricity test. Explicit instructions, which of course, made the analogy evident, resulted in a significantly higher rate of carryover in the explicit groups.

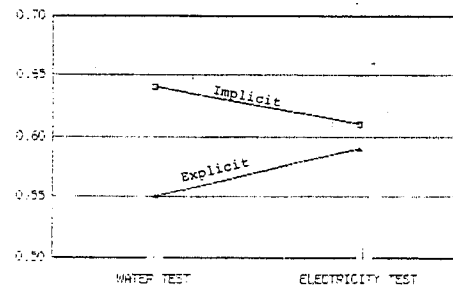


#### Performance

The accuracy of responses on the first trial of the water test (the baseline trial) and the electricity test can be seen in Fig. 3. The pattern of results for the training and no training groups was statistically indistinguishable, suggesting that the training variable had no effect. A comparison of the implicit and explicit groups, on the other hand, revealed a substantial difference. Subjects who were not told about the analogy (the implicit groups) showed the same decline in scores from water to electricity observed in Experiment 1, while those who were given explicit analogy instructions (the explicit groups) achieved scores on the electricity test that were comparable to, or even better than, those on the original water test.



AVERAGE PROPORTION CORRECT ON FIRST TRIAL OF  
WATER AND ELECTRICITY TESTS -- TRAINING



#### Reaction Time

Analysis of the reaction time measure provided further support for these findings. Once again, training had no significant effect. Explicitness again served to reduce the domain effect. Subjects who were not told about the analogy, showed the same tendency that was observed in Experiment 1 to devote more time to the water than to the electricity problems. This difference was reduced significantly, however, when subjects were instructed to think about electricity in terms of the water analogy.

#### Relationship between Detection and Performance

We expected that the correlation between carryover and target performance would be high for subjects who received training in the base domain, since training would increase the likelihood that those responses that were carried over would be the correct ones. In fact, the correlation was virtually perfect ( $r=.913$  for implicit-training;  $r=.904$  for explicit training).

The results of experiment 2 mirrored those of experiment 1. Increased familiarity with the base domain was not sufficient to ensure the discovery of a potentially useful analogy. However, as in experiment 1, increased familiarity did improve the usefulness of the analogy if detected. These results suggest that familiarity with the base domain affects the power rather than the accessibility of an analogy.

#### General Discussion

The experiments reported here have been concerned with the issue of analogical transfer: What causes a particular analogy to be accessed in the course of problem solving? The issue is an important one because previous results have shown that novice problem solvers often miss a relevant analogy, even when that analogy would provide a solution to a problem that they are

trying to solve (Gick & Holyoak 1983). The present experiments extend these findings by demonstrating that performance on a test of electric current was not facilitated significantly by prior exposure to an analogous test in the more familiar domain of waterflow. In all of these studies, there was a striking contrast between the low degree of spontaneous transfer and the high degree of benefit if transfer occurred. Potential analogies were missed even though they would have been powerful tools for problem solving.

Given the power of these analogies, it is intriguing that they were so easily overlooked and that we were unable to increase analogical transfer by manipulating the familiarity of the base domain through prior experience (Experiment 1) or through training (Experiment 2). The intuition behind the present set of studies was that subjects with more exposure would show more transfer. The results suggest, however, that "mere exposure" may not be enough. Instead, experiences are needed that lead the learner to make comparisons that promote the discovery of invariant relationships. This characterization of the ideal state of knowledge for making analogies is reminiscent of recent discussions of expertise. Expert knowledge has been characterized as highly organized, clearly represented, abstract, and domain independent (Forbus & Gentner, 1984). What appears to be important in both analogical transfer and in the development of expertise is not familiarity per se, but rather the opportunity to redirect attention to the relevant higher order relations (Gibson, 1969).

To foster expertise and encourage analogical thinking a training program will need to redirect attention rather than just provide exposure. One effective way may be the use of multiple analogies (Gick & Holyoak, 1983). Secondly, abstract relationships can be taught directly (e.g., through mathematical formulas). This kind of training, however, may be difficult for the novice and result in a mechanical plug-into-the-formula approach to problem solving rather than good intuitive understanding. In summary, there are few shortcuts to the development of expert problem solving skills, including the ability to detect powerful analogies.

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THE IMPORTANCE OF WATERCIRCUITS IN TEACHING ELECTRIC CIRCUITS

Hannelore Schwedes

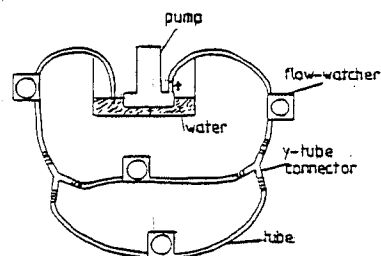
In her review of recent research Andrée Tiberghien has given a summary of the basic investigations and results on students' perceptions and preconceptions in the field of electricity. The main interest of this research was to analyse the students' current intensity and voltage concepts and to examine the relations between the variables  $U$ ,  $I$ ,  $R$  in students' minds. Besides the lacking idea of current conservation there was mostly missed a developed concept of the electric potential. It tends to be confused with the current concept and often there is seen no difference between the two concepts of current and potential. Andrée Tiberghien concludes in her review "that instruction places too much emphasis on electric current and favours a sequential reading" (p.123). Our statement, however, is that the students' understanding of the current concept itself hasn't yet been investigated thoroughly enough.

The result of our studies on students' interpretations of watercircuits is, that instruction does not care enough about pupils' conception of flow. There is a lack of insight into the causal necessity of current intensity in the sense of a scientist. Many misconceptions established in the field of basic electricity can be found, too, in the arguments of students discussing our water models. A sequential argumentation is also used by our students when disputing about the various effects seen in our watermodels. But these watercircuits are also bearing the chance to lead the students to a global argumentation. They can learn to look at these watercircuits as a whole system and to combine local and global reasoning.

Our water models (fig. 1) were designed for instruction. We had the idea that students need good acquaintance with the model itself before they can use it for drawing conclusions from the system, which is figured by the model. This could be done best if students could handle those water models themselves. So, in contrast to most models used in (basic) electricity instruction, our watercircuits are qualified for the students' use in their



experiments. Differently structured circuits are easily built up.



The flow-watchers are resistors and at the same time flow meters showing the speed of the passing water.

Figure 1: Water-circuit

As we try to construct curriculum devices that can be called an autotelic educational environment, we have developed a lot of problems, experimental tasks and games with the elements of these watercircuits so that the students can gather much direct experience with the watermodel and its various structures. Acting themselves they can construct circuits according to their own ideas. (Schwedes/Schilling, 1984 u. Aufschneider u.a., 1982). By inviting students to make their assumptions explicit there can arise cognitive conflicts when students' expectations don't hold true and they feel the need for an adequate explanation. Observing students in the classroom, we were struck at the great difficulties the students had in understanding how the water circuits work. So we evaluated systematically the perceptions, conceptions and theories our students used to explain the different velocities of the flow-watchers in those water circuits. We gained our results from records of classroom instruction, from clinical interviews and from written tests. The age of the students ranged from 10 to 16 years but there were found no basic differences between the younger and the older students when confronted with our water circuits. Our principal procedure was nearly always the same. We asked students to make predictions about the current intensity at various points of the water circuits or the velocity of the various flow-watcher balls and to give reasons for their

predictions. Then the pump was switched on; differences between predictions and observations were discussed, and the students were asked to explain the unexpected experimental results. The predictions usually had the form "This one (this flow-watcher ball) will spin around slowly, very slowly, fast, very fast or this one will be faster (slower) than that one. Sometimes we additionally asked for an estimation of the amount of water flowing through at certain points of the circuit in a unit of time. In those cases normally the current intensity at the pump was given, sometimes the current intensity in a branch of the circuit.

### Series Circuits

A typical pattern of prediction for a series circuit is shown in fig- 2.

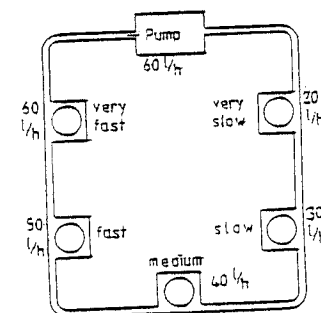


Figure 2

The mostly given arguments for these predictions are:

"The impetus of the water decreases with every obstacle (flow-watcher). It is the same with a rolling ball: at first, when you have just pushed it, it rolls fast and then it slows down". "The pump is driving the water and here, next to the pump, the water is fast. Here, far away from the pump, the water is slow". "The further away the water is from the pump (the active element) the slower it is". "When you pour water out of a bucket it is the same. At first there is plenty of water and it is pretty quick and then it gets slower and less and cozes". Comparisons with various obstacles are made (hurdle-race, revolving door, water-wheel).

When students observe those five flow-watchers in a series circuit they notice that they all show the same velocity of the circulating ball i.e. of the water flowing through. But unfortunately these striking observations of a real experiment do not alter the students' ideas in the expected way. Most of them insist on their type of local argumentation; before the impediment the water has power, high speed, and after the impediment the water is inert and slow.

An example may illustrate these difficulties. After a long discussion with their teacher, in the course of which they learnt that there comes back to the pump the same amount of water as the pump ejects, students made the following predictions for the series circuit:

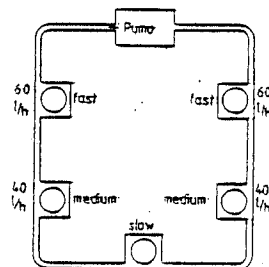


Figure 3

The students explained: the pump is pressing at one side and sucking at the other. They did not reflect on where the water was left before the (second or) third flow watcher nor where the water would come from after it (the third or fourth flow-watcher). This may indicate that we meet here with a well established pattern of explaining the movement of water. Beyond this we can assume a concentration on one variable, the speed, which is the obvious one, as Piaget has found in many other cases, especially in his investigations of conservation.

After several lessons on watercircuits 75% to 85% of the students gave the right predictions for series circuits. In circuits with parallel branches the students also recognized flow-watchers joined in series when they were built in. They gave right predictions in so far as they said that all flow-

watchers in the same branch would indicate the same speed and that in a branch with these flow-watchers the velocity would be less than in a branch with only two of them.

This knowledge most likely comes from the direct experience with those water circuits. The students' most common arguments for these "new" judgements are: "The flow-watchers have the same velocity because they are arranged one after the other", "There is no branching off", "The same amount of water must run through all flow-watchers".

We think that these explanations are given more on the grounds of a practical knowledge of how to manipulate the elements of the watercircuits than they are based on an insight into the conditions of flow (on the level of flow continuity, current intensity and value of resistance). For nearly all the students who, after a while, had good success in the prediction of series circuits like those of fig. 2 failed at the following task of investigating the effects of a pressing clamp. The students had to predict the velocity change of each of the flow-watchers if at a certain point the tube was pressed together a little bit by a clamp. The previous patterns of interpretation re-appeared and students only looked at the clamp as a local event. The following three types of standard responses were usually given:

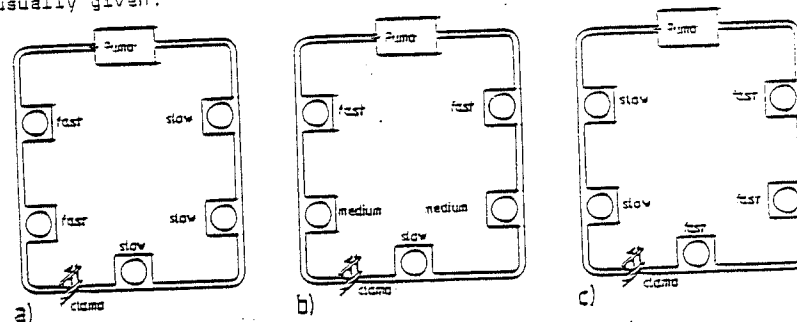


Figure 4 : Students predictions for water-circuits with a pressing clamp

The argument for solution (a) was: The water runs with un-reduced velocity up to the clamp where it is dammed, it loses

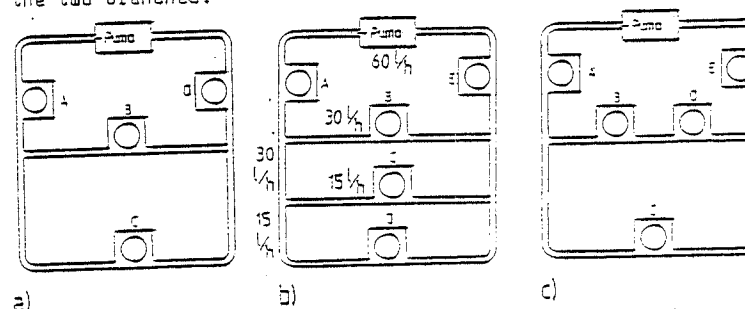
its power and behind the clamp it's running slowly like a weak inert stream. Students, whose answers resembled type (b) focus the clamp as an actor of disturbance. From the clamp the irregularities start spreading out to both sides. Some students compare the situation with an accident on a motorway. The car slows down approaching the narrow pass and having passed (the area of the accident), the car will accelerate again. Students transpose themselves onto a moved particle of water, see the event of being squeezed, and follow the fate of the water-particle. Finally, students with type (c) responses consider the pressure in the circuit. In front of the clamp the working pump causes an overpressure so that behind the clamp the water will splash out with high speed. It's the same when you take a hose to water the garden; if you squeeze it at the end, the water will rush out in a high curve. In all these cases the students don't see the watersystem as a whole. They don't see that the system is closed. They treat the system as if it were open and concentrate on the local event of being pressed. They expect a change of velocity only at some flow-watchers and this depends on the model chosen from former experience for the required explanation. The students have not yet become aware of the principle of continuity, which characterizes the process of the streaming of fluids. Although this principle is locally valid, too, for the model of an open watersystem, there is normally no need to become aware of it. The speed is the dominant variable and no attention is paid to the amount of water before and behind the narrowing of the clamp.

Yet, with our watercircuits this problem can be tackled. The permanent questions: "How much water? Where is the water left? Where does the water come from?" will finally lead the students to grasping the principle of continuity that means: the amount of water that arrives at a certain point also has - not more not less - to leave it again, and for a closed, unbranched circuit: the amount of water, that arrives at a certain point also arrives - not more not less - at every other point of the circuit.

### Circuits with parallel branches

To complete the given picture I want to add some examples of how students assess the velocity of the water at different flow-watchers in watercircuits with parallel branches.

As in circuits like that of fig. 5a many students argue with the distance from the pump in their first approach. The flow-watcher (C) which is the furthest away from the pump is the slowest one (compare fig. 2). When students construct a circuit as in this diagram, they often cannot explain what they observe. A hint to the point of ramification usually helps. Now the students can infer that the flow-watchers B and C are slower than A and D because the full amount of water is divided up between the two branches.



a) b) c)  
Figure 5: Water-circuits with parallel branches and a typical prediction of current intensities in 5 b

Changing from two to three branches in parallel most students will give predictions like that in fig. 5b. At the first point of ramification the watercurrent divides into equal parts, one half flows through the first branch, the other half divides again. When these students observe that the flow-watchers in all three branches show the same speed, they often develop a mainstream model. They perceive the structure of the circuit as a ladder. Through the two beams on each side there flows the total current (30 l per minute) and through each of the three rungs here flows a third of it (10 l per minute). It seems difficult to imagine an asymmetrical partition at the point of ramification. This can be verified, too, in circuits like that of

fig. 5c. Here, too, at the branching point the current is normally divided up into two equal parts.

In fact these problems are not easy to solve. Finding the right solution requires the connection of local and global arguments. When students don't take the pressure of the water into account, which is, indeed, dispensable in their reasoning they have to see at least that the flow-watchers, more exactly the number of them, determine the current intensity in each branch (local argument). But at the same time they have to realize that there exists a sort of feed-back (global). Already at the first point of ramification the water "feels" that there are still following another two branches in parallel or that there are following two different branches with different resistances. In short they have to look at the circuit as a system.

#### Discussion

There are a lot of hints that students normally don't use current intensity in the clear cut meaning of the physicists' definition. In general they apply it to a broad range of situations in everyday life and they use it in a wide, rather unprecise sense, relating sometimes more to the velocity of the water and sometimes more to the amount of it. They make use of the variable that obviously dominates the observed situation. Similar results are reported in the investigation of P.J. Wilkinson: "When, however, one is altered, in this case a decrease in cross sectional area, the compensation, by increase in speed, is rarely seen in other than rather vague intuitive terms. Thus half are aware of the dependence of rate of flow upon both the amount passing across a certain section and the time taken for this to occur, the precise relationship between the two factors cannot be handled". We assume that the missing concept of current intensity is strongly related to the lacking principle of flow continuity. Perhaps before the concept of current intensity can be established it is necessary to have grasped this principle.

When we review the mistakes, misconceptions and preconceptions which students activate in explaining our watercircuits, we notice a striking similarity with students' representations

of electric circuits: the current intensity, which is decreasing from resistance to resistance in a series circuit (the catcher model), the current, which is consumed, the current which is running off both sides of the source (pump or battery) (sink model), the mainstream model, the difficulties in realizing that the total current intensity is the sum of the current intensities in the parallel branches, the students being restricted to sequential argumentation and the inability to see the circuits as a system.

From this we derived the hypothesis that many misconceptions in basic electricity originate from a defective model of streaming water. This assumption is supported by the investigation of Gentner et al who could show that high-school and college students, who were novice learners in physics, especially in basic electricity, used streaming water models for interpreting electric circuits. They particularly applied conclusions they inferred from the water model to the electric circuit. This was most striking when mistakes that came from a defective water model were transferred to incorrect statements on electric circuits.

Maichle explains students' failing understanding in basic electricity on the grounds of inadequate schemata, which students use understanding the electric process (but which are inadequate in this context). In her investigations she has identified three working schemata: the GIVE-schema, the TAKE-schema, which can both be classified as a TRANSFER or TRANSIT-schema and are matching well with the sink-model, and the DISTRIBUTE-schema. These schemata are spatially and/or temporally organized cognitive structures, which represent knowledge and which are the units of perception and comprehension processes. They have been elaborated from past experience, probably very early in the individual's learning history on the basis of concrete actions. So they are well established and normally very effective in every day life. Hence, it seems quite possible that the misunderstanding of the streaming processes in the water circuits originates in the inadequate use of these schemata. Further research will show this. If the schema hypothesis is right, our watercircuits are another good example to confirm the efficiency of these schemata and to investigate how those

schemata are chosen in the process of understanding.

In the summary of his investigation J.L. Closset points out the possibility that sequential thinking is connected with schemata that are well established before instruction. Perhaps the dominant approach of sequential reasoning derives simply from the fact that all actions have a sequential organization and that in planning actions the temporal sequence has to be put well into consideration. If so, it is not surprising that sequential reasoning doesn't disappear as a method of problem solving and is generally used when new, difficult situations are to be mastered. J.L. Closset suggests to avoid sequential argumentation in the instruction process, to implant suspicion to sequential reasoning and to base electricity instruction on global argumentation such as the concepts of potential difference or energy. Contrary to that we propose to combine the local view with the global view of the system as a whole, where the global way of consideration has to be learnt first. Our water circuits, however, seem to be good objects to develop a global argumentation. The contact with the streaming process is much more direct in the watercircuits than in the electric circuits.

To summarize, using water models in electricity instruction without teaching the students intensely about the model itself won't make much sense. On the other hand will an incorrect watermodel increase the difficulties in understanding the basic electrical concepts. If one considers the language, the usual expression "the current flows" or "is streaming" implies already a liquid-model for the electric current. Because of this and other reasons we have decided to teach explicitly and detailed about the needed water model. We won't agree with Kircher who admits the watermodel only the status of an aid; we think that instruction on our water models has a right of its own.

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"Teaching electricity : interactive evolution of representations, models and experiments in a class situation"

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## I - Introduction

We present below some relevant elements of an experiment about teaching electrokinetics (D-C.) in grades 6, 8 and 10 of the French curriculum (12, 14 and 16 years old).

### I.1. Hypothesis and cognitive aims

Our main hypothesis was that the "metaphor of a moving fluid" is a basic representation of the phenomena in electrokinetics. Following this hypothesis, we attempted :

- to build a more correct "circuit model" [1]
- to discriminate between the two distinct notions of potential and current
- to promote reasoning in "potential terms", useful to go beyond the "constant flow" models, mostly applied to tension generators [2]
- to clarify the double role of "conductor" and "hindrance" played by resistor [3].

In this paper, we do not specifically treat problems linked with sequential reasoning [4,5] beyond the aspects described above.

### I.2. Introduction of analogic models

We learn using what we already know, and this process is often a long and complex one [6].

Using analogies is one of the ways currently put into practice by the learner, even if it is not the explicit purpose of the teacher [7]. The teacher can legitimately ignore this fact, though he knows of it [8]. We made the opposite choice : using analogies systematically in teaching electrokinetics (D-C), we attempted to verify if they promote better models and reasoning.

Among the analogic models structurally similar to electrokinetics [9], three must be quoted :

- a) the hydrodynamic model first presented by Maxwell (1856) [10]. As

several studies showed that the concept of pressure is more or less as complex as the concept of potential [2], we did not keep it within the aims determined above.

b) the thermal model which was the first to appear giving the framework to establish Ohm's law (1827) [11].

c) the mechanical model, presented below.

### I.3. The role of experiments

In the French curriculum, the teacher conceives, proposes, carries out some of the experiments. The students have to do some others and their role is limited to : "observing the phenomena", and rarely guessing explanations. Elucidation and drawing the conclusion is essentially left to the teacher, so preconceptions and types of reasoning by the students are never taken into account.

On the contrary, it may be interesting :

a) to give a central role to the models and explanations of the students, the proposal of new problems remaining the responsibility of the teacher.

b) to transform the "private" nature of the relation between the observed phenomena and the models of each student with debates between the students themselves. We call this method "scientific debate in the class" (see [12] for further details about social psychology).

c) to give a test role to the experiment, allowing a choice between previous hypothesis, eventually contradictory, put forward by the students from their own models.

### I.4. Comparative questionnaires

This procedure has been tested in several classes, and its effects compared with the evolution of a set of equivalent normal classes. Our principal tool was a test-questionnaire including 44 items about simple electric circuits (D-C), before and after teaching.

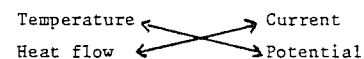
### II - The thermal analogy

Here, temperature plays the role of electrical potential, and heat flow that of current. As a difference of temperature causes a heat flow, a difference of potential causes a current flow. From a psycho-cognitive view point, the concept of temperature difference appears as simple enough,

likewise the "causal relation" temperature difference  $\rightarrow$  heat current.

On the other hand, the concepts of heat and heat flow seem to be difficult to understand correctly [13]. So we get the inverse situation of that which exists in electrokinetics where current is spontaneously separated as a concept but not the potential.

Thus we proposed a "cross" introduction of thermal-electrokinetics, the corresponding concepts occupying an inverse place in a difficulty scale for each domain :



The thermal circuit used was an ordinary device : a refrigerator. A thermal generator maintains a constant difference of temperature between the inside and the outside of the refrigerator (getting an exact analogy with the electric battery). As defects (holes) exist in the supposed perfect thermal insulator, some "thermal" leaks exist. The electric circuit is then presented as a way allowing electrical leaking of the current : so students spontaneously made the analogy : a larger or smaller "hole" in the thermal insulator corresponds to an electrical conductor whose resistance is smaller or greater.

This introduction to a resistor as a way through which an electrical current can flow appeared very fruitful in the case of derived circuits. This "crossing" introduction was tested in several classes of grade 10 and its effects compared with the evolution of equivalent normal classes. The first results are in process of analysis, but seem to be promising, at least concerning the cognitive aims quoted above.

### III - Example of relationships between students conceptions/models/debates/experiments.

#### III.1. Presentation

Another experiment was carried out in 3 classes of grade 6 and 2 classes of grade 8. It concerned the whole curriculum in D-C electrokinetics for these grades in French colleges. We only describe here the 5 first sequences of 1 hour, in fact common to the 2 grades.

Students were first asked to light a bulb using a battery and 2 electric wires. Then the teacher asked the following question : "How (or why) does it work ?"

### III.2. First answers of the students

a) Three kinds of answers rapidly appeared :

- an "one wire" model [14] relatively fleeting, although some traces remained further on in the curriculum (we shall call it "model A").
- a "clashing currents" model, which was predominant in grade 6 and yet present in grade 8 (called "model B").
- a "circuit model" where students did not emphasize current loses through the bulb ("model D").

b) The public debate :

These different models were clearly expressed by the pupils (in fact model A was rapidly abandoned) and the class entered a real debate. But this one progressed essentially by criticising the "adverse opinion", much more than presenting arguments in favour of his own model. However this process led to some changes in opinions, essentially to greater accuracy in the model to take into account the adverse "attacks". In this way, the following argument was opposed to model B : "Why would we need two wires ?". This led the B students to add a new generalizing precision : "Because there are two electricities, plus and minus".

The evolution of the D defenders was more spectacular. They were challenged by the following major criticism : how could they take into account the wearing of the battery (anticipated by the whole class) ? Then, the "lose of current" when passing through the bulb was added to the model, although it was not present in the initial form (this new model is called "model C"). From a cognitive point of view, this must be described typically as a progress (contrary to what a physicist may think) towards a greater coherence of the model, according to the previous knowledge of the students.

### III.3. The role of experiments

The question, now, was to discriminate between these alternative models. All the classes found (on their own) that it was necessary to answer two distinct questions :

- what is the direction of the current in each wire ?
- what amount is passing through the two "ends" of the bulb ?

a) In one grade 8 class, the teacher proposed the use of two zero centered ammeters (as Osborne did [15] (see Fig. 1).

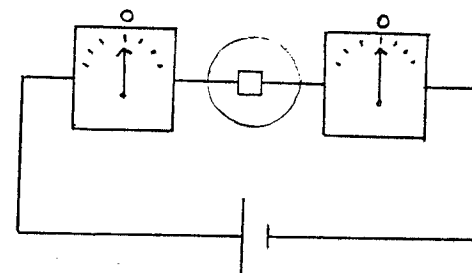


Figure 1 - Circuit with 2 central zero ammeters.

Before experiments, the students had to anticipate the results in hypothesis B, C or D. Their answers were astonishing : the most frequent anticipation was that, in case B (clashing current model), the hands of the ammeters would move in the same direction. In fact, this is really coherent with their previous believes : the two currents are seen as moving in two parallel ways, in the same sense ! (see Fig. 2).

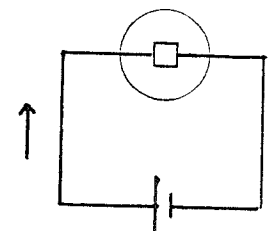


Figure 2 - Two parallel ways in the same direction in the case of "clashing currents".

b) Since this experiment was ambiguous, we had to use two distinct experiments :

- exp  $b_1$  with a compass for the direction
- exp  $b_2$  with two ammeters for the current (see Fig. 3).



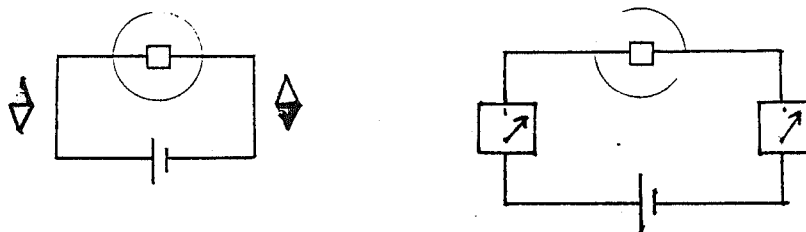


Figure 3 - Two experiments to introduce a correct model.

When experiment  $b_1$  was done, the whole class immediately abandoned model B, and united by supporting model C. Nobody considered model D. In grade 6, the students refused this model as not relevant. So experiment  $b_2$  was not necessary : the whole authority of the teacher was needed to try it.

c) The result stunned the grade 6 classes. At first, the experiment was discarded, with the following "arguments", never used previously : the ammeters were broken, false, they did not show "exactly" the same reading, their positions had to be inverted, the bulb had to be changed, and the teacher himself was even accused of "falsing" the experiment ! We can explain such a reaction by the following arguments :

The passage from "B" to "C" models is very easy because these two positions worked and debated by the students, seem equally reasonable. So the experimental judgment is assumed without difficulty. On the contrary, model "D" is judged unrealistic according to the arguments debated previously. The students are so confident in their model that they refuse the experimental evidence.

#### III.4. Analogy as a paradigmatic frame

a) The interpretative arguments (and not phenomenologic ones) given by the students against model D were so strong that they had to be answered before the students would accept even the simple reading of an ammeter. To do that, it was necessary to know the conceptions of the students:

- the quasi-unanimity most likely used a "moving fluid metaphor", but this image remained extremely indistinct at least within these sequences. In the following lessons, we noticed the presence of "static

models" for current [16,8], as soon as open circuits were discussed.

- this fluid had, at the same time, a material and an energetic nature. So, the students could not understand how it could light the bulb and remain identical with itself. It was necessary to take into account this fundamental objection (without forgetting the other aims quoted in the introduction).

b) For that purpose, we used a mechanical analogy : the circuit was compared to a railway track, entirely occupied by rigidly bound carriages. We can summarize the analogy :

|                   |   |                                        |
|-------------------|---|----------------------------------------|
| current intensity | ↔ | displacement velocity of the carriages |
| bulb              | ↔ | hindrance on the track                 |
| battery           | ↔ | workers pushing the train              |
| electric tension  | ↔ | pushing force                          |
| battery weariness | ↔ | muscular weariness                     |

There is, in fact, a double aspect in this analogy :

- a formal and structural one
- a metaphorical one, which saves the basic ideas of "circuit", and of a "moving fluid" (see Fig. 4).

c) The introduction of this analogy brought about a spectacular effect : the absolute rejection of model D disappeared almost instantaneously. All went as if a genuine change of paradigm (in the sense of Kuhn [17]) had happened and, at the same time, a real acceptance of the experiment tested before.

d) Of course, other analogies can play the same role, but this is not the place to compare the advantages and disadvantages of each one. Concerning the "train analogy", the utility of its metaphorical aspect appears easily ; the students are given a relevant example of differentiating "2 fluids" material and energetic, and they are given a good aid to establish a "circuit model" (the carriage velocity is the same at each point of the track).

However, this utility would be quickly used up if it were not relieved by the structural aspect of the analogy, which, alone, can allow it to develop as a real model, permitting for instance the analogic introduction of EMF, and its differentiation from current (this is not

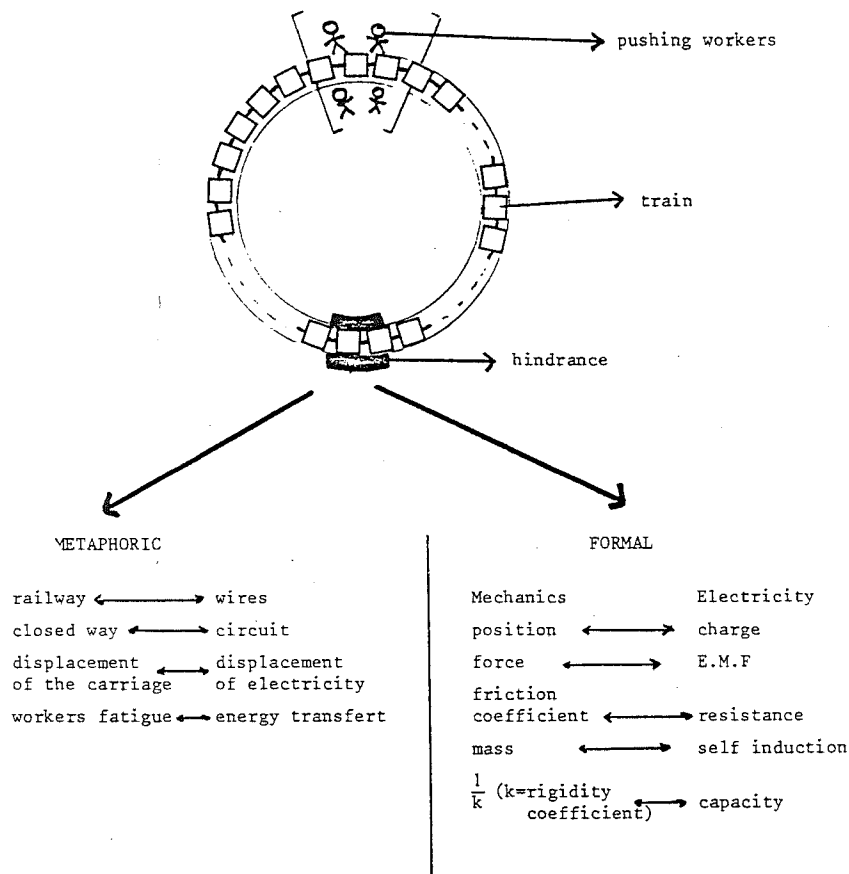


Figure 4 - "The train analogy" : metaphorical aspects and links with the mechanical analogy.

developed in this paper). That solid basis furthermore would allow the model to last and to gain in precision when applied to different situations (this was our purpose in the following sequences). But two limitations in this method appeared as essential :

- the mechanical analogy allowed the introduction of EMF, but not "local potential". So very serious problems arise when studying derived circuits (difference from thermal analogy),

- the mixture "formal model-metaphoric analogy" presents some risks (for instance : "What happens if the wire is cut ?") and requires that the teacher carefully leads the students to clarify the limitations of the analogy. But a working model/experience is indeed possible and this is a fact to notice (remember the students are 12 to 14 years old).

In the above example of "cut wires", many of the students guessed (referring to the metaphorical aspect of the analogy) that the bulb would be put out, but after being alight "just a bit longer". A wire was actually cut in a real circuit, and, from the immediate extinguishing of the bulb, the students easily deduced that "all was going as if it was a train, it was not a real train, neither a real railway".

Of course, this is not perfectly solid. Many returns to a misconception were noticed in the following sequences. But, each time this happened, the reference to the "train analogy" allowed the correct conception to be reached quicker.

### III.5. Evaluation by comparative questionnaires

Here again the progress of the experimental classes appeared to be quite noticeable in comparison with equivalent normal classes. This was true even for classes considered as "generally weak" (complete results to be published).

### IV - Some final considerations

This does not establish any "superiority" of our proposal at all. Other models, analogies, methods without analogy may be as efficient as ours (and, indeed, they are so !). Furthermore, we would have to decide what is relevant to the method, and what to the applied exercises, and to... the devoted teachers ! We would have to test the long term solidity of supposed acquisitions. In this study, we only wanted to test the self consistency of our initial hypothesis (and this seems to be positive) and to show the interest of our type of approach to overcome difficulties which are beginning to be shown by a lot of studies.

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## THE ELECTRIC CIRCUIT AS A SYSTEM

Hermann Härtel

### 1. The development of the "IPN Curriculum Physik"

Since the beginning of the curriculum work at the IPN in the late Sixties, the electric circuit has been one of the central topics. It has been treated within different projects and still is of interest in research and development.

In the first part of the curriculum, written for children aged 11 to 12 years, the objectives are centered on the topological structure of a simple electric circuit, where the two terminals of a batterie and a resistor have to be connected (see Duit's paper on this topic in these proceedings).

In the second part of the curriculum (published in 1973), written for pupils aged 14 to 15 years, the terms voltage, current and resistance are introduced in a more systematic and rather conceptional way, using measurements as procedures to define terms.

In a third part (published in 1975), written for students aged 16 to 17 years, different models of the electric current were developed to treat in more detail the idea of model construction in physics and to reach deeper understanding of the basic terms in electricity.

### 2. Outcomes of the curriculum

When looking at the effects of these different parts of the curriculum, it was found that just for the first part the outcome was satisfying or could be tolerated. Pupils of that age like to play with batteries and bulbs, they quite easily grasp the idea, that a closed circuit is necessary and they are quite clever in building combined parallel and series circuits and making them function (see some more details in Duit's paper mentioned above). However, the teaching of physical terms like current and voltage turned out to be no

more successful than the usual textbook teaching. The students did not understand the meaning of the measurements, they could not grasp the relation between the different terms, and Ohm's law still had to be learned by heart if it was learned at all.

### 3. Arguments for a new concept

The search for reasons to explain this failure and to give hints for new and better concept development brought three main results, which can be stated in a short and simplified manner as follows:

(a) The structure of the electric circuit with its elements and its associated terms, as it is found in normal textbooks, as it is represented in the minds of most teachers, and as it is presented and explained to students, cannot be really understood i. e. new and old knowledge cannot be integrated. One can only get used to it by a lot of exercises and learning it by heart, hoping that real understanding will come later on. The definition and the presentation of a physical term as the result of a measurement like

$$\text{Voltage} = \frac{\text{Energy}}{\text{Charge}}$$

or

$$\text{Resistance} = \frac{\text{Voltage}}{\text{Intensity of current}}$$

is a method to demonstrate the elegance of the physical method, its exactness and clearness. Such a method is, however, a shortcut of the historical development of these terms within the development of science. It suppresses the qualitative relationships of these terms, thereby blocking or hindering real understanding.

(b) Students' preconceptions about the electric circuit, its elements and its functions determine their learning and understanding in a very dominant way.

Such preconceptions are described in more detail in other

papers of these proceedings. Some important ones are:

- The battery is a source of current.
- The current is consumed while running through the resistor.
- The events caused by the current are related to local interaction of the moving particles and the resistor, the lamp, the motor or the like.

The current is treated like a system, where single, unconnected particles are moving around. Even in modern textbooks this idea is supported by making an analogy to loaded and unloaded cars running around on a highway.

There, local interaction, an accident or a traffic jam, can block the incoming cars only. Those who have passed already can no longer be influenced by that event. So this local thinking leads to a sequence of events in only one direction.

For the electric circuit follows that the moving particles can only influence those elements of the electric circuit which are in front of them.

It is not understood that the circuit is really closed and that it does not make any difference if a moving particle is in front or behind a resistor.

(c) These preconception cannot be changed by the simple demonstration of a so called crucial experiment, accompanied by the correct interpretation. These preconceptions are rather stable and in many cases they are blocking the possibility of making observations and of drawing conclusions in accordance with physical theory.

### 4. The system aspect of the electric circuit

One of the main reasons that the electric current is so hard to understand and so difficult to teach is seen in the fact that local or sequential thinking is so dominant in our everyday experiences.

It is even found in the explanations of physical phenomena and relationships in modern textbooks as the following model shows (from the US Curriculum "Probing the Natural World").

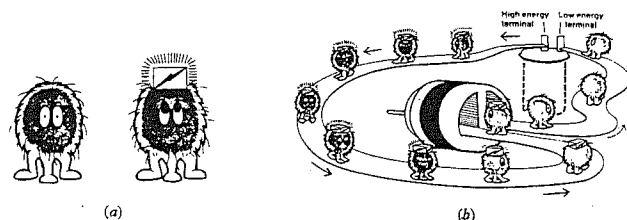


Figure 1: A misleading model

- (a) Electroparticle without and with energy  
(b) Model of an electric circuit

In this model the single particles are emphasised, while their interrelations are not visible. From this model, for instance, one has to draw the conclusion that the 'empty' particles which have passed the motor, cannot be influenced by any event behind them.

This model therefore will support local or sequential thinking and will lead to serious difficulties if students take this model as background and start asking questions. There is another example where explanations in physics support sequential thinking: the long and tiresome discussion about the direction of the current flow. When a teacher is pointing out that the current is flowing from plus to minus (or from minus to plus) he or she inevitably supports local or sequential thinking.

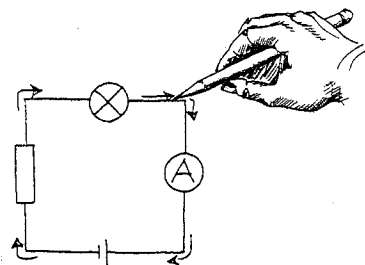


Figure 2: Demonstration of current flow

In daily life there is not much experiences with systems with very strong relationships between all the elements and where these relationships are visible or will be observed. The electric circuit however is a system where every point depends on all the others and influences all the others. The formal expression of this fact is Kirchhoff's 2nd law.

$$\sum_i U_i = 0$$

Thus it is understandable that many students who never could built up an idea of a system will not be capable even of reaching a starting point for understanding.

It seems necessary to activate first a new schema as a background for understanding by explicitly treating the system aspect for adequate mechanical or hydromechanical systems as a bicycle chain, a stiff ring or a water circuit.

The discussion of such systems in comparison with the preconceptions based on local thinking should be helpful supporting understanding and ones own thinking.

Moreover the treatment of an electric circuit as a complete system - similar to a stiff ring - is most adequate to explain and to describe all the different phenomena. In the process of teaching, this structure has to be developed further. It has to be shown that the bicycle chain is only a model to start with. It is a rather limited model because it needs a frame to function and there is only a pull on one side of the chain. The stiff ring is a bit better, because there can be a push on one side and a pull on the other. But again a common frame (ground of the earth) is necessary for this system to transport energy.

Inevitably there is a moment when the analogy with mechanical objects leads to contradictions. Field forces acting on a distance are different from short range contact forces between mechanical particles. But the fact, that every point is in-

fluencing all the others and is influenced by all the others remains true and has always to be considered.

Based on these consideration a teaching unit was developed (Stromstärke, Spannung, Widerstand, 1981). This teaching unit was described in the European Journal of Science Education (Härtel 1982). For further details the reader is referred to these publications.

##### 5. Supposed results of the new concept

Until now there has not been a systematic evaluation of long lasting effects of this new approach. From observations during the trials and from discussions with teachers using this approach, there are three points worth mentioning.

(a) The changing of preconceptions of daily life experiences and the building up of new concepts is a tedious process which requires much time and much effort. The possibilities of falling back are numerous and it needs a lot of understanding and patience on the side of the teacher to give constant and fruitful support during this process.

(b) The system approach, the accentuation of the interrelation of all parts of the circuit and the constant search for the closed circuit which moves as a "stiff ring" is a good tool to give this required support. It helps to convince the students to change their own ideas and to start their own thinking about the various objects, processes and outcomes.

(c) It is not very likely that even with this teaching concept there will be many long lasting effects on students knowledge.

Probably these effects will be small when just tested by questionnaires or other similar evaluation instruments some time after instruction.

There are two reasons for this presumption.

First, the preconceptions about electricity and the electric circuit are permanently supported by experiences in daily life. These preconceptions are reinforced all the time, be-

cause they do not lead to apparent contradiction. So it is not astonishing that these conceptions are the dominant ones, which are found again in follow-up tests.

Secondly, the electric circuit as a topic for tedious study is just not very attractive for a large part of students aged 14 to 16. There is no real connection to their life, the terms and rules to be learned are abstract and without any meaning to them. Only for those who are involved in electronics can the knowledge about electric terms be relevant for directly improving their actions and products.

So it seems to be quite natural that most of the objectives which are reached during instruction and which can be tested in the final examination will soon be forgotten. A better way of evaluation than just applying a follow-up test would be to measure the time of instruction, necessary to brush up the knowledge to a satisfactory level.

It is hoped that teaching the system approach will lead to rather short refresher courses necessary to remind the students of the "stiff ring" and all the consequences for current flow, parallel circuits, etc. However, the evaluation to prove these assumptions has still to be done.

##### 6. Computer-simulation to support understanding

In his book "Mindstorm, children, computer and new learning", Seymour Papert has demonstrated the use of the computer as a microworld, where only one single idea is demonstrated without any side-effect or complex surrounding.

It seems to be possible to adapt this idea to the electric circuit, particularly in respect to the system approach. At the IPN a program in machine language was developed to simulate the movements of a dotted circle with different velocity according to the applied "voltage".

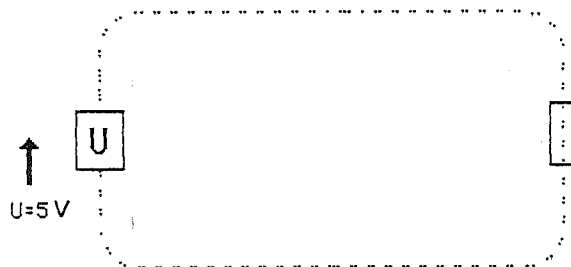


Figure 3: A simple electric circuit

Five resistors of equal size can be applied in series or can be removed and each time the velocity of the moving ring is changed according to Ohm's law. One resistor - the sixth - can be placed in parallel, so that even a combined circuit can be demonstrated.

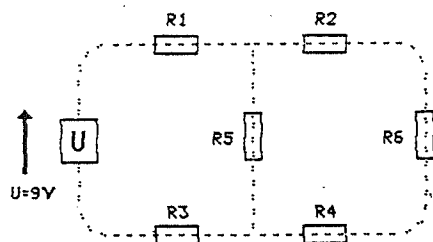


Figure 4: A combined electric circuit

A second program has been developed to simulate the properties of flowing matter at a branching point. It has been found out, that students do not normally see the relation between incoming and outgoing currents and that the application of the continuity condition is not at all simple.

To help and support teachers while explaining these relationships, a simulation program was developed. It shows the flowing matter symbolized by a drift of vibrating points at variable density and velocity passing through the branching point.

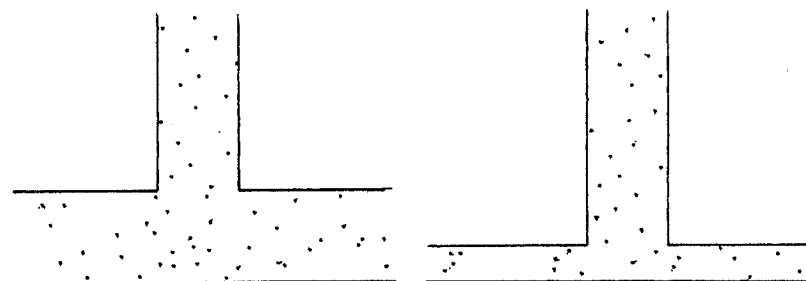


Figure 5: Vibrating points drifting through a branching point

The diameter of the outgoing tubes can be changed and as a result the drift velocity of the points is changing in accordance with the continuity condition.

For stimulation of thinking and reflection the program can be altered in a sense that the gas is highly compressible. In addition a program loop is included where the continuity condition is no longer valid. New points are created or a fraction of these disappears at the branching point. All these programs are proposed as a medium to support teaching by using less words and yet leading to better concentration on the central points of concern. The message for a student could be something like:

"This is a way in which you are allowed to think and you will come up with good and reasonable results. Later you will have to develop this structure in different aspects but for the first beginning it is a good starting point."



The message should never be something like:

"This is a true and final picture of what happens within the circuit. If you have understood this, you will find any explanation you want without further problems."

These programs of course should not replace experiments with real objects and they cannot replace the own model building and reflection.

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The simulation programs are written for an Apple II computer. They can be ordered from the IPN by sending an empty discette together with a return envelope.

#### THE ELECTRIC VOLTAGE

What do students understand?

What can be done for a better understanding?

Hermann Härtel

#### 1. Voltage and electric field

The term voltage belongs to the most difficult ones within the physics curriculum at lower secondary level.

In contrast to current, which can be related to something which is moving, the physical background of voltage or potential difference are electric fields where no mechanical analogies can really hold. Though the concept of a gravitational field is a fundamental one in mechanics, it has little meaning for everyday experiences. Students at lower secondary level usually have not developed any other concept than mechanical particles in empty space, where interaction is linked with direct contact. So these students can hardly grasp the idea of voltage or potential difference between two points when there is no visible or even thinkable difference between these points. Because of this fundamental difficulty, all teaching efforts for students of that age are bound to fail when aiming at a deep and full understanding. All attempts which do not include an explicit and careful treatment of the field concept, but which take support from mechanical analogies, can only explain the effects in parallel and series circuits on the basis of plausibility, as in the following argument:

If the pressure difference at the ends of parallel waterpipes is the same, why should not the voltage over two parallel resistors be the same?

It is this kind of reasoning that can help to make things more familiar and plausible. A deeper understanding, however, cannot be reached by this method.

## 2. Voltage and pressure difference in a water circuit

The term pressure as  $\frac{\text{Force}}{\text{Area}}$  is in itself difficult and is normally regarded by students as a special force in a certain direction (opposite to pull). Moreover, the pressure along a water circuit is a complex function of different parameters. The question is whether this analogy can be helpful while teaching electricity and especially voltage, when it is so difficult in itself?

Our experience has shown that this difficulty can be reduced by the following means.

First we take as analogy a closed water circuit under high pressure but with a very low flowing rate.

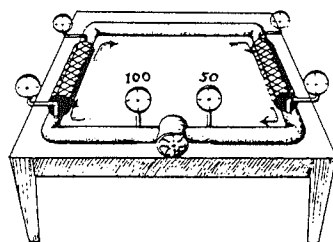


Figure 1: Representation of a water circuit

This latter condition is not only necessary to avoid any turbulence and to simplify the pressure measurements along the tubes. It is also necessary to make the analogy to the electric circuit as close as possible. Fast running water has kinetic energy which has to leave the system when the waterflow is switched off. The kinetic energy of electrons however is negligible compared to all other interaction processes. So a current can be switched off with almost no energy dissipation.

There is a second possibility to simplify the teaching of pressure in a water circuit: The introduction of flexible tubes. In the unit on "Current, Voltage, Resistance" of the IPN Curriculum (1981) we have used the picture of a water circuit where the tubes were rather flexible and where the differences in pressure could easily be observed.

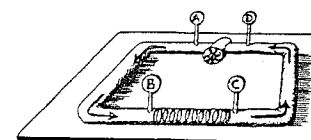
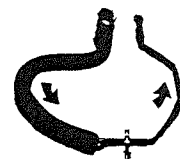


Figure 2: a) Water circuit with rubber tubes

b) Representation of a water circuit

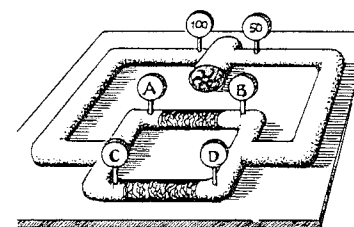
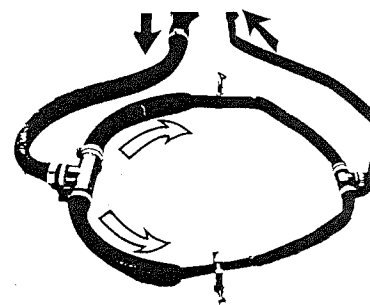


Figure 3: a) Parallel water circuit with rubber tubes

b) Representation of a parallel water circuit

These pictures have proven to be quite fruitful in discussing pressure measurements along a water tube. In particular, the students could be convinced that the pressure along the tube connecting the pump and the resistor is (nearly) constant.

This finding is a big step because in many cases the students are convinced that the pressure at the entrance of the resistor is much higher than near the pump.

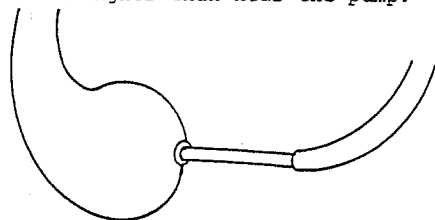
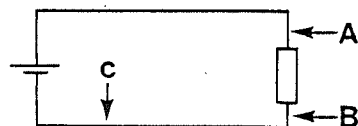


Figure 4: A typical student drawing of a water circuit with rubber tubes

### 3. Surface charges in electric circuits

The difficulty connected with the understanding of the term voltage can be demonstrated with a rather simple question:



Why do I measure a voltage across a resistor - point A and B - and practically no voltage between point B and C? The three cross-sections seem to be identical on a microscopic scale. The same amount of electrons with the same drifting velocity are passing through as follows from Kirchhoff's first law.

Most textbooks explain that there is a potential difference between these two points. But what corresponds to this difference in microscopic dimensions? There is even the same electric field and in a super-conductor this field is even zero. This problem is, of course, not one of the physical theory. The problem is that many teachers and high school

students cannot give a satisfying answer to this rather simple but basic question.

It is an astonishing fact that physics education has overlooked a rather simple explanations for this question: the existence of surface charges, accompanying any current flow within a conductor. The existence of these surface charges are described in some textbooks and in some articles. In most cases, however, they are not mentioned. The reason for this lack of attention to an existing physical phenomenon may be found in the fact that these surface charges are rather small and normally not detectable.

The loyalty to the principle that only measurable terms are allowed to enter physical theories may have led the teachers and textbook writers to look only for the drifting electrons within the wire and to declare the distribution of these moving electrons uniform and neutral.

It is proposed in this article to change this attitude and to include a complete study of all effects connected to surface charges into the curriculum of electricity, especially when the term voltage is treated.

This proposal does not mean, that this new topic has to be taught to all students at lower secondary level. The lack of a field concept, as it was mentioned at the beginning, is again a severe barrier in understanding the behaviour of charges, their mutual interaction and their effects over long distances. However, the study of these surface charges seems to be necessary for physics students and teachers for at least two reasons:

- It may help to clarify their own ideas about voltage, potential, etc.
- It may show teachers the complexity of the so-called "simple electric circuit" and may lead to more careful and adequate teaching with better anticipation of the existing difficulties in learning and understanding.

- And last but not least, there may be some students who really want to know more about voltage and potential and who will not go on without a satisfactory answer. In this case details about surface charges and their influence on all the other parts of the circuit may give substantial support in encouraging further studies and in creating or maintaining curiosity.

#### 4. Proposals for teaching material

The theoretical background about surface charges and electric fields around a current-leading conductor has been treated in textbooks, for example in Rosser: Classical Electromagnetism via Relativity (1968). They have been rediscovered and further developed by Walz (see his article in this publication). Therefore the following remarks do not intend to give a complete and exact representation of the phenomenon with the best fit to all existing theories. The interested reader is referred to the above mentioned publications.

The pictures and explanations that follow intend to give an initial and simple demonstration of the discussed phenomena as they could be presented to teachers, students or others. In any case they have to be developed further. It has to be stressed that these pictures are exaggerating a very, very small effect, as can be seen by the following calculation: If one calculates the extra surface charge at the edge of a conductor, which is necessary to reflect a current of  $10^{19}$  electrons per second at an angle of  $90^\circ$ , the result is  $\sim 1$  single electron.

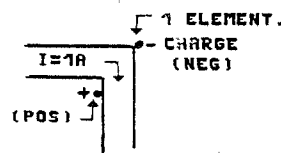


Figure 5: A current of 1 A  
benched by 1 Electron

The ratio 1 to  $10^{19}$  is negligible in praxis but not in theory, because without this single electron it could not be understood why the movement of the electrons forming the main current is reflected by  $90^\circ$ .

For the demonstrations of surface charges along simple electric circuits we have developed some simple pictures to start the discussion and to support individuals' own thinking. These pictures can be drawn on transparencies or on a computer screen. The latter method is more comfortable because it allows individualization and it is easier to handle.

In the following, all effects corresponding to interaction of surface charges on different wires (electrostatic induction) and geometrical conditions like curved wires etc. are neglected.

First it has to be pointed out that a normal copper lead consists of an equalized amount of positive and negative charges (figure 6 a).

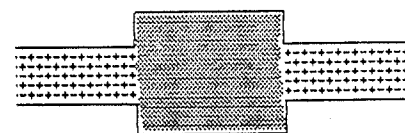
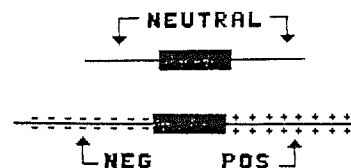


Figure 6:

a) A resistor with leads  
without a current



b) Representation of a  
resistor with leads with  
and without surface-  
charges

Surface charges connected with a current flowing through a resistor are symbolized as shown in fig. 6 b.

As Walz has shown (see his paper in this proceeding) a surface charge distribution according to

$$\sigma = \sigma_0 + c \cdot x$$

renders an axial and homogeneous electric field within a straight wire, where  $x$  is the coordinate in the direction of the current.

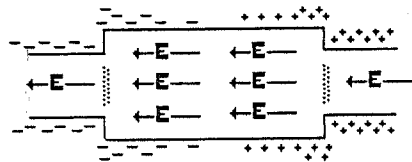


Figure 7: Change in the distribution of surface charges

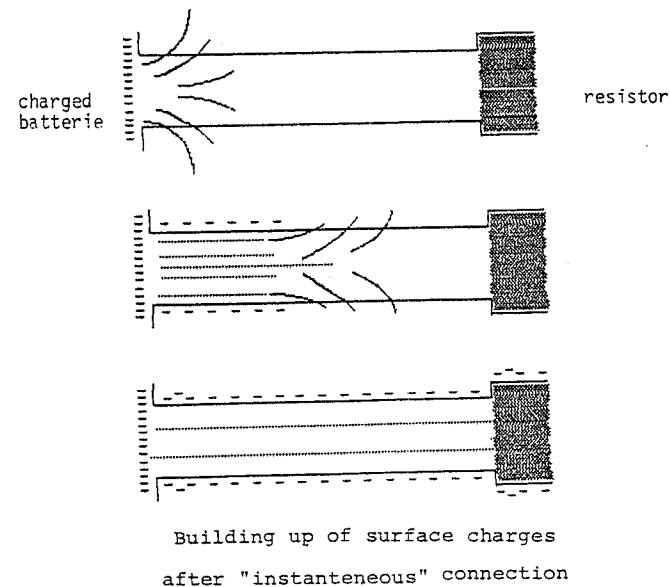
According to the change in conductivity in the copperwire and the resistor, the constant  $c$  is changing, giving a different gradient in the surface charge distribution and therefore a different field within the copper and the resistor.<sup>+</sup>

It may even be helpful to consider the process which builds up these extra charges on the surface of a wire and on the resistor after the battery is connected to the circuit (see fig. 8).

Neglecting any transient effects due to electrostatic induction, one has in the very first moment a nonaxial electric field in the wire. This field will cause some electrons to move to the surface until the electric field is bent to the axial direction. Due to the small gradient in the distribution of the surface charge, the axial field within the copper lead is reduced to the steady state value (according to  $j = E \sigma$ ).

<sup>+</sup> Volumes charges within the region where the conductivity is changing (dotted area) are neglected to simplify the representation.

Figure 8:



For a circuit with resistors in series or parallel the distribution of surface charges for steady state condition can be symbolized as follows:<sup>+</sup>

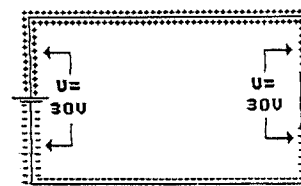


Figure 9:  
Surface charges on  
a circuit with one  
resistor

<sup>+</sup> Computer programs to visualize these effects in a dynamic form are being developed.

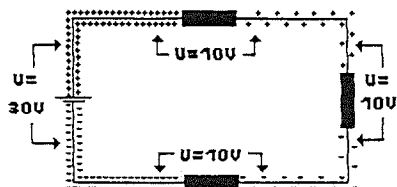


Figure 10:  
Surface charges on  
a series circuit

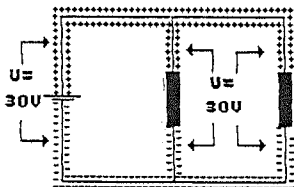


Figure 11:  
Surface charges on a  
parallel circuit

Again it has to be stressed that these pictures are exaggerating and simplifying a rather small effect. But this small effect together with the field concept is necessary for understanding. Having reached this point the students should quite easily rely on Ohm's law and Kirchhoff's law for further studies for this should make their work easier and more effective.

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## CONSTRUCTION OF CAUSAL MODELS: EXPERIMENTING WITH CAPACITOR-CONTROLLED TRANSIENTS AS A MEANS OF PROMOTING CONCEPTUAL CHANGE

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### THE BATTERY-CENTERED MODEL

My work as a physics teacher reminds me every year how hard it is for students to visualize the crucial role of electrostatic forces in electric circuits. The field model of electrical causality, which is proposed in physics textbooks, seems remote from my students' experience of actual circuits. These students are well aware, however, that batteries are essential for the operation of electrical devices. Thus, they find it natural to adopt a battery-centered causal model [1] for explaining circuit phenomena.

According to this model, batteries are the sole sources and the sole agents of propulsion of a mobile substance that is responsible for circuit operation. The substance does not act on itself while in an external circuit, and its presence there has no effect on a battery's rate of emission. Connecting wires are regarded simply as hollow pipes through which this passive substance is transmitted.

Research on students' reasoning about electric circuits has revealed major misconceptions which are closely related to the battery-centered model. Consider some of the conclusions from two recent comprehensive studies:

Closset [2] finds sequential reasoning across a wide variety of circuits. Effects in series-connected circuit components are imagined to be coordinated by simple forward transmission. There is no feedback due to interaction with components situated farther downstream.

Cohen, Eylon and Ganiel [3] find that current is the primary concept used in reasoning. Resistance can be imagined as obstructing but not as drawing current. Potential difference is regarded as a consequence of the flow through resistors, rather than the cause.

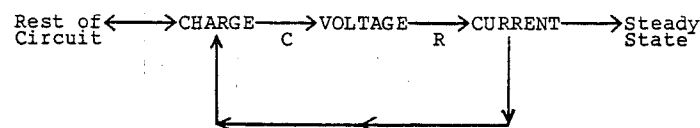
These misconceptions are enormously at odds with the field model of electrical causality. It is truly impressive that they should persist after formal instruction at the high school or university level.

#### THE IMPORTANCE OF TRANSIENTS

I propose experimentation with transient phenomena as a remedy for this situation. The approach was suggested by my classroom experience with bridge circuits -- for which sequential reasoning fails to provide intuitive solutions.

I have found students keenly interested in how a bridge circuit gets to a new steady state after a switch is closed or opened. They prefer to avoid formal analysis of the final steady state until its causal legitimacy has been clarified. They sense that insights essential for understanding steady-state behavior are hidden in the fast transients that precede the establishment of steady states.

The hidden insights can be brought to light by noting that a resistor's connecting wires constitute a capacitor in parallel with it. The rest of the circuit exchanges charge with this "stray" capacitor by competing electrostatically with it, while the charge on the wires simultaneously drives a three stage feedback cycle. I'll diagram that cycle by drawing an arrow from each cause to its effect and noting effects mediated by capacitance  $C$  or resistance  $R$ :



The feedback cycle for each resistor commences whenever a change of circuit parameter unbalances the previous electrostatic equilibrium with the rest of the circuit. The cycle repeats until the current through every resistor has reached a new steady state. The three stages are:

1. Charge-voltage causality -- The charges on the connecting wires cause a potential difference, whose magnitude is determined by the capacitance of the wires.

2. Voltage-current causality -- The potential difference between the wires causes a current through the resistor, whose magnitude is determined by its resistance.

3. Current-charge feedback -- The current through the resistor alters the charges on the wires, which leads to further charge exchange with the rest of the circuit.

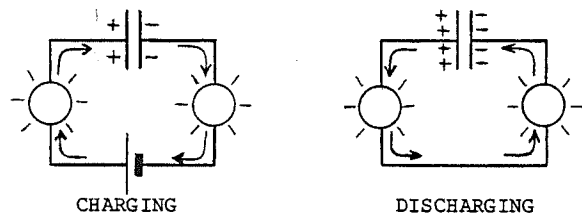
The diagram reveals that a great deal will remain hidden if the transients initiated by parameter changes are too fast for human perception: Students will be unable to observe feedback effects which provide the evidence that changing concentrations of electric charge on the wires are affecting the current through the resistor. They will then have no evidence at all of charge-voltage causality, and could fail to grasp the meaning of "potential difference" in the context of voltage-current causality. They will be aware only of batteries as causes and steady currents as effects, leaving them vulnerable to sequential reasoning.

#### RESOLVING BASIC ISSUES

I propose to promote awareness of charge-voltage causality in electric circuits by introducing intentional capacitors into circuits of batteries and light bulbs. [4,5] Capacitors should provide the most direct possible evidence of this causal relationship, because they determine how charge is distributed in a circuit. Of course, one needs enormous capacitance to stretch out the time scale of transient bulb lighting for purposes of human perception.

But that is no problem for today's technology, which can provide up to one whole farad in a small nonpolar unit.

I'll introduce my approach by demonstrating a capacitor charging-discharging experiment. Note that the bulbs light up during discharging, when there is no battery in the circuit. Students readily intuit that something becomes stored in the capacitor and then pushes itself back through the bulbs. The important question arises: Back to where?



The arrows on these diagrams indicate the direction of the current. Notice that the arrows point out of one capacitor plate during charging. This implies that the moving substance originates in metallic materials -- and thus in wires, too -- as well as in batteries. It implies that current in wires is due to replacement flow of a substance which is always present whether moving or not.

The evidence is that a battery strives to push this mobile constituent into a nonequilibrium distribution, but that capacitor charging is opposed by increasingly strong forces of electrostatic origin. During discharging these forces push the displaced substance away from the plate containing an excess amount labelled (+) and toward the plate containing a deficit amount labelled (-), that is, back toward electrostatic equilibrium.

These inferences weaken the authority of the battery-centered model. Consider the conceptual change I recorded in a class of 18 high school students. I asked two questions before the students experimented with bulb-lighting transients, and again after they had observed these phenomena, and then again after class discussion of

the implications: (1) Do the light bulbs use up any of the substance that reaches them through the wires? (2) Does the battery squirt out more of this substance at one end than it takes back in at the other? Here are the responses (with one absence at the third round of questions):

|                  | Do the light bulbs...? |    |           | Does the battery...? |    |           |
|------------------|------------------------|----|-----------|----------------------|----|-----------|
|                  | Yes                    | No | Undecided | Yes                  | No | Undecided |
| Before observing | 18                     | 0  | 0         | 18                   | 0  | 0         |
| After observing  | 18                     | 0  | 0         | 7                    | 6  | 5         |
| After discussion | 3                      | 14 | 0         | 2                    | 13 | 2         |

Belief in the battery as a current source declined at each stage. The resilient belief in light bulbs as irreversible absorbers also eventually dropped dramatically.

#### ELECTRIC POTENTIAL: COMPRESSIBLE FLUID MODEL

For students of high school age, I propose a causal model which attributes the self-action of the nonequilibrium charge in capacitor plates to a pressure-like condition in a compressible fluid. The fluid pressure is HIGH in the plate in which an excess amount (+) is compressed and LOW in the plate with a deficit amount (-). The fluid is pushed from the site of HIGH pressure to the site of LOW pressure. [6]

This intuitive conception of electric potential is very appealing to students, and they enjoy calling it "electric pressure". Its force-related character makes it readily available for causal reasoning -- a very favorable contrast to the abstract energy-related conception which is usually associated with the electrostatic field model.

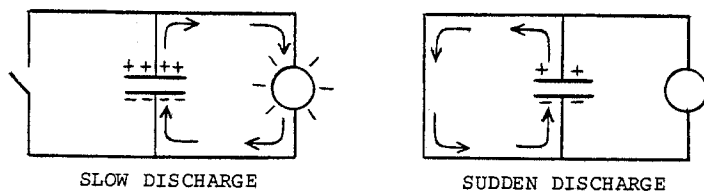
#### RESISTORS AND WIRES

Conceptualizing resistance in the limited sense of obstacle makes it hard to understand how adding resistors in parallel can draw current from a battery. A subtler conception can be generated by observing the different amounts of time required for discharging a capacitor through



light bulbs having different resistance values. A shorter discharge time is due precisely to less resistance drawing more current at the same voltage.

I'll use a modified discharging experiment to demonstrate that connecting wires have essentially zero resistance. One simply short-circuits the capacitor while it is discharging slowly through a light bulb and observes that the bulb turns off suddenly, as in these diagrams:



The very important equipotential property of wires follows from the zero-resistance property: Since a wire cannot sustain a difference of "electric pressure" for a significant length of time, it will in practice always be found to have uniform "pressure". Because a resistor can sustain a potential difference, however, its connecting wires may have different uniform "pressure" values.

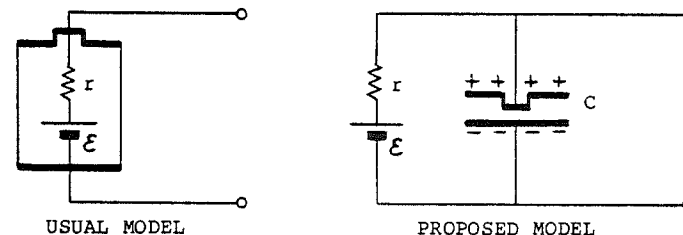
Wires emerge from this experiment as the most active of all circuit components, because they reduce potential differences to zero in a negligible amount of time. This conclusion must be unsettling to anyone who had previously thought of wires simply as hollow pipes.

#### BACK TO BATTERIES

A battery's electromotive action on mobile charge may be studied through its competition with the electrostatic self-action of that charge. An electromotance value may be assigned by measuring the final or asymptotic "pressure" difference the battery can generate across a capacitor. The capacitor voltage is measured directly with a voltmeter,

whose response has previously been clarified by application to capacitor charge sharing experiments. The rate of discharge through the meter will be negligible if the capacitance values are sufficiently large.

These experiments suggest that a battery should be modelled to include the capacitance  $C$  of its own metallic terminals, as well as its internal resistance  $r$ . The electromotance  $\mathcal{E}$  may be thought of as striving to maintain the same potential difference across this "stray" capacitor as across any intentional capacitor. The fact that the electromotance property determines only the asymptotic voltage explains why the actual voltage may be less in an operating circuit where there is leakage from the capacitor.



#### ELECTRIC POTENTIAL: ELECTROSTATIC FIELD MODEL

I would now like to turn to the field model of electrical causality, in which potential difference is customarily defined as "work done per unit charge". This energy-related definition is poorly suited to causal reasoning. I propose to generate a force-related definition by generalizing the "electric pressure" idea to a conception that can encompass action-at-a-distance forces in non-conducting media as well as contact forces in conductors.

A capacitor dielectric may be modelled as a network of identical series-connected resistances  $R$ , in the non-conducting limit  $R \rightarrow \infty$ . Since the spatial distribution of "electric pressure" values is independent of  $R$ , the limit

$R \rightarrow \infty$  yields a distribution of values which is suspended in the nonconducting space between the capacitor plates.

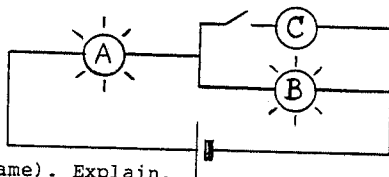
Is this distribution of what might be called "potential electric pressure" -- or perhaps "electric potential" -- values real? Does it actually push test particles in the HIGH-->LOW direction? An affirmative answer may be obtained by charging two capacitors connected in series with a light bulb between them. The experiment demonstrates that the "electric potential" concept can indeed explain the appearance of a voltage across a light bulb which is separated from the battery by nonconducting gaps.

The use of the compressible fluid model as an intermediate conception in this process of generalization calls to mind the use of short skis as a temporary substitute for long ones in modern skiing instruction. [7]

#### FURTHER CONCEPTUAL CHANGE

Is the ability to take feedback from downstream components into account enhanced by experimenting with transient phenomena? Consider the responses of three groups of students to the following problem, at the end of one year of physics instruction:

The bulbs are identical, and A and B are glowing. When the switch is closed, bulb C also glows while bulbs A and B become (brighter, dimmer, same). Explain.



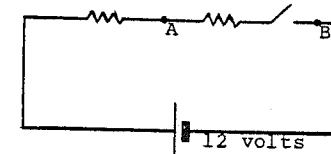
The correct answer is that A becomes brighter and B dimmer. The students' responses were:

|                  | Subjects | Correct Answers |
|------------------|----------|-----------------|
| College Class X  | 21       | 10 = 48%        |
| College Class Y  | 49       | 2 = 4%          |
| University Class | 62       | 4 = 6%          |

Note that the percentage of correct answers is very much greater for college class X than for the other classes. The only intentional difference between the two college classes is that class X experimented with capacitor-controlled bulb lighting, while class Y did not. Neither did the demographically quite different university class. These data clearly support the view that experimenting with transient phenomena has a positive effect on ability to take feedback from downstream circuit components into account.

Is reasoning about feedback a higher level cognitive skill, which can be exercised only after sequential reasoning is abandoned? Consider the responses of college class X to a second problem:

The two resistors are identical, and the switch is open. The voltage across points A and B is \_\_\_\_\_ volts. Why?



I have identified the sequential reasoners from their responses to the previous problem. I'll use the term "feedback reasoners" to describe subjects who solved that problem correctly, because they successfully accounted for feedback from downstream circuit components, and I'll use the term "intermediate reasoners" to describe those who tried to do this but did not succeed. Unfortunately, only the data from college class X are usable because the number of feedback reasoners in the other two classes is too small for meaningful analysis.

The correct answer is of course 12 volts. Here are the responses of college class X:

|                        | Subjects | Correct Answers |
|------------------------|----------|-----------------|
| Sequential Reasoners   | 7        | 0               |
| Intermediate Reasoners | 4        | 1               |
| Feedback Reasoners     | 10       | 5               |

Note that none of the sequential reasoners arrived at a correct answer, while half of the feedback reasoners were able to do so. Of course, larger samples and additional ways of probing the issue will be needed to draw a firm conclusion about stages of causal reasoning. Nevertheless, these data suggest that the experience of capacitor-controlled bulb lighting promotes conceptual change by first posing a challenge to sequential reasoning.

#### REFERENCES

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2. J.-L. Closset, Le Raisonnement Séquentiel en Electrocinétique. Doctoral thesis, University of Paris VII (1983).
3. R. Cohen, B. Eylon and U. Ganiel, Potential Difference and Current in Simple Electric Circuits: A Study of Students' Concepts. American Journal of Physics 51, 407 (1983).
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#### CAPACITOR PURCHASE INFORMATION

##### 5,000 microfarad capacitors

These are nonpolar and nonelectrolytic (maximum 20 volts). They are useful for rapid charging-discharging through high resistance light bulbs (40-50 ohms).

Melvin Steinberg will send two samples gratis to anyone who wishes to try them. He will ship larger numbers at \$3.50 each within North America or \$4.00 overseas (by air).

To obtain 60 capacitors or more (minimum purchase \$200), order directly from the manufacturer:

Mallory Capacitor Division  
Post Office Box 372  
Indianapolis, Indiana 46206  
U.S.A.

Ask for Part Number TCG502U020N3L1N.

##### Large-value capacitors

These are nonpolar, but electrolytic with some equivalent series resistance. They are useful for slow charging-discharging -- for example to exhibit resistance comparison, capacitive bridging, and voltmeter response to charge sharing by two capacitors.

They may be purchased in any quantity by requesting "Supercaps" from suppliers of NEC (Nippon Electric Company) electronic components:

|                            |                         |
|----------------------------|-------------------------|
| 1.00 farad (max. 5 volts)  | Catalog Number FA0H105Z |
| 0.47 farad (max. 10 volts) | Catalog number FA1A474Z |
| 0.22 farad (max. 10 volts) | Catalog number FA1A224Z |
| 0.10 farad (max. 10 volts) | Catalog number FA1A104Z |

The 0.47 farad Supercap is probably the most versatile one.

# USING COMPUTERS IN TEACHING ELECTRICITY

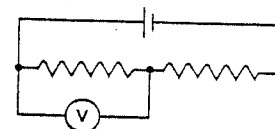
Raphael Cohen

Microcomputers are being more and more standard equipment in high schools in my country, and I believe that this is true for all the Western World. There is more than one reason for this. Not only the feeling that any student should consider the computerized world of tomorrow as a friendly world, and be prepared to it; and not only the obvious use of computers for learning management, like exams. There is also some kind of mystical belief, that computers should be the key answer to the decline of teaching and the mean lowering level of the students population, particularly in Sciences. One of the best known physics teachers in France, involved in development of teaching by computers, told me last year that he foresees almost all classes being taught by computers by the turn of the century, because there will be by far, not enough physics teachers by this time.

The problem of physics teaching is certainly an acute one, that has to be solved by various means. But I do not believe that computers are the answer to it. The best that computers can do, until now, is to improve skills and practice, like doing arithmetics or flight simulation. There is a lot to do in this area in physics also, but this is not teaching.

Most of my students learn Basic, and it seems to me a pity not to use this as a help for learning electricity. I had to find how. I did not intended to prepare some problems on a diskette and have them solved by the students, because this does not look to me a better way than a book. I wanted students to use computers only for problems that gave them mathematical difficulties. Here are the problems that I found adequate to be solved with computers

I)



If we look at this very simple circuit, we see that the reading of the voltmeter depends on the ratio of its resistance to the resistances  $R_1$  and  $R_2$  in a complicated mathematical way. Most of the students fail in doing the algebra, the analysis give the formula

$V = E \frac{R_1 R_V}{R_1 R_2 + R_1 R_V + R_2 R_V}$ . It is possible to do a very simple program with the three resistances as Inputs, that performs the calculation of  $V$  and gives to the student the feeling of the influence of  $R_V$ . The program may also draw a graph of  $V$  versus  $R_V$  or  $R_1$ .

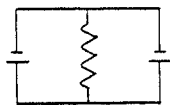
II) When connecting a variable resistance to a battery with internal resistance, the p.d. of the battery varies according to the formula

$$V = E \frac{R}{V + R}; \text{ the power developed as heat in the external resistance}$$

$$P = \frac{E^2 R}{(r + R)^2}. \text{ These are two mathematical functions that are not known}$$

very often, and again a very simple program can display their graphs. The second graph will enable the student to see that there is a maximum when  $R = r$ , a very important theorem in load matching.

III) A more important project is making a program to solve a set of linear equations. At least the program should be able to solve a set of 3 equations with 3 unknowns, so that it can be used to solve simple circuits by the means of Kirchoff laws, like this



IV) A very simple way that leads to numeric solutions of differential equations is met in the charge or discharge of a capacitor. Looking at the discharge first, we can see that

$$\frac{q}{C} = Ri = -R \frac{\Delta q}{\Delta t}$$

$$\Delta q = -q \frac{\Delta t}{RC}$$

$$\text{and } q_i = q_{i-1} + \Delta q$$

A small program will give  $q = q(t)$  and make a graphic display of it, then it is obvious to see that the same kind of graph gives also  $V = V(t)$  and  $I = I(t)$ .

For the charge of the capacitor, we see that

$$E - \frac{q}{C} = Ri = R \frac{\Delta q}{\Delta t}$$

$$\text{so } \Delta q = \left( \frac{E}{R} - \frac{q}{RC} \right) \Delta t$$

$$\text{and } q_i = q_{i-1} + \Delta q$$

again the program makes a graphic display of  $q = q(t)$ , and the same kind of graph gives the p.d.  $V$  on the capacitor. The graph of the current is made by using  $i = \frac{E - V}{R}$ , and allows the students to see that it is the same graph as during the discharge.

V) Finding the R.M.S. value of a p.d. or a current is a very good example of calculation of an area under a curve, and a straightforward exercise in Basic.

VI) Drawing the graph of the current in a coil connected or disconnected to a source is the same kind of work that has been done with capacitors.

VII) The most interesting program that can be made is the simulation of LC and RLC circuits, without or with an external AC source. This seemed to me too difficult for my students, so I made a program on a diskette. In this program (in Hebrew) there are three parts. The first one deals with LC circuit and the student can change the parameters and see the display of the graph of current as a function of time. In the second part a resistance is added, and the student can play with its value and see the graph of the damped oscillations. In the third part an external AC source is added to the circuit in series, and the forced oscillations can be seen on the screen, the student can change the frequency of the external source, and reaches the notion of resonance.

These are indeed very few points in all the electricity program, and suggestions how to widen the use of the computer would be happily accepted. One of the ideas I don't know how to realise, is to use a computer for simulating experiments in DC circuits. (It would be safer and cost less than real experiments at the beginning).

Most of the students that learned Basic found interesting and enlightening to do the programs I proposed. They felt improvement in their computer's skill and understanding of the problems they solved.

# THE USE OF COMPUTERS AS A STUDENT DATA CHECK

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Fitchburg, MA. 01420 (USA)

Introduction: The phrase "Computer Literacy" is viewed by some curriculum planners as pure advertizing hyperbole and by others as the most serious challenge of the eighties. The issue has not been ignored by physics educators evidenced by the publication of three major articles relating to laboratory applications of microcomputers in The Physics Teacher (see Chonacky and Ingoldsby (1984), DeJong and Layman (1984), and Rafert and Nicklin (1984)). Personal-computer enthusiast magazines are beginning to include technical articles for educators (see Gates (1984)). Three of the articles just referenced describe situations in which computers were used as direct data-gathering and data-manipulation (arithmetic and plotting) devices in experimental situations - usually with respect to time. Undoubtedly, these applications are attractive in that they demonstrate the technological strength of computers.

The purpose of this paper is to propose yet another use of the computer as a pedagogical device; one which allows the student to check the validity of laboratory data both with respect to the accepted standards as well as to the findings of other students. This paper will present both the cognitive science basis for the application proposed, plus a detailed discussion of a BASIC program with which the goal may be met. I make no evaluative comparison between this application and the use of computers as laboratory instruments.

The Process of Learning Physics: We know precious little about how people learn anything - physics included. In spite of the fact that a number of cognitive scientists have presented models of human information processing, and a number of researchers have presented data both on how "successors" succeed and the current learning system "fails", there is little consensus among educators on appropriate learning prescriptions for success with the standard learner.

Unquestionably, most Introductory Physics courses are carefully planned and executed. Nevertheless, data provided in Fredette and Lochhead (1980), Clement (1982), Fredette (1981), and Steinberg (1984), to name a few, suggests a need for curriculum planners to rethink the foundations upon which such courses are built. The data described in these papers suggest that students make serious errors when asked to

apply physics knowledge to some supposedly simple problems. Riley (1983) describes several investigations in which learners were encouraged to consider physics problems given them in terms of associated broader or more general concepts. She reports data which suggests that problem-solvers enabled to create their own general conceptual framework succeed more often than those not so enabled.

The specific computer application being described here was partly generated in response to a conviction that learning takes place best when there is a sense of context for the learner; this is consistent with the cognitive development model of Piaget as well as the "Whole-Parts Schema" described by Riley. It was also initiated in response to the data referenced in the previous section (Fredette et al).

This author's research and experience suggest that many students come to the laboratory expecting explicit directions on how to proceed, as well as a specified number of measurements or evaluations to be made. These students do not expect to evaluate either the quality of their own work or its context in terms of any other work required for the course. If one of the goals of education is to empower people to be self-directing and self-critical then a problem must exist.

One solution is to alter the usual pattern of interaction between student and instructor. I am suggesting that the student be required to take an active role in deciding what ought to be done next. The instructor's role becomes one of creating an atmosphere which allows for "professional" urging or providing facilitatory help where appropriate.

The Laboratory Problem which Utilizes Program GRAVITY: An experiment common to most first semester introductory physics courses is one in which the student is asked to determine the rate of acceleration associated with some vector component of the earth's gravitational force. The prototype computer program to be discussed was designed for this class of experiments and is titled "GRAVITY".

GRAVITY's role enters with the student's independent determination of "the answer" to the problem assigned; in this case, the answer is the rate of acceleration of some rolling or sliding object down an inclined surface for at least one trial. Then, in what may be considered a non-threatening encounter (GRAVITY has no part in the student evaluation), the student presents the computer with both raw data and

the calculated result. In return, he or she is given a report on the quality of the work by comparing results with those considered standard (expert) in addition to those for the same experiment as performed by other students. As students were invited to examine the computer analysis of their data, I noticed several changes in their laboratory work patterns; the most important being a questioning of the outcome of the experiment. Many were stimulated to redo the experiment trying out some new personally-devised technique.

Student Use of GRAVITY in the Laboratory: Figure 1 is a typed version of the material which would normally appear only on the video screen of the computer as the program is "run". The program output was planned for an 80 column by 24 line screen (standard for CP/M operating systems). This author has added labels and bracing which cue the reader to the various program features.

Information included in the section braced by the label "A", which ought to be part of any stored program put into use infrequently, is intended for the instructor. At the very beginning of the program run, a message appears on the screen listing all reminders necessary for use of the program in the particular setting.

The section braced by the letter "B" represents the beginning encounter between student and computer. Information provided in this section will be used to identify the data to come. Rather than distinguishing the data by person or experimental team, it is grouped according to apparatus. This choice makes it possible to ask students to comment on whether or not "better" results can be associated with any one procedure in particular. Grouping according to apparatus also discourages attempts to personalize data quality. More will be said about the value of identifying data in a neutral way later. The number "70" in the line "This trial ...70" is set by the program with each new student input incrementing this value by one.

Data (numbers only) provided by the student may be found in the series of boxes within the section braced by the letter "C". Unless the programmer is clever enough to employ "screen codes" for data entry (the procedures used by writers of "spread-sheet" programs), alteration of data which has been entered on some previous line requires a specific option such as the the last line of this section. If the student enters a "0" at this query the computer runs through its prompts one more time

## PROGRAM OPERATION NOTES:

'999' at DEVICE input will dump to disc  
 '10' at DEVICE input will dump all data to printer  
 ---SET BAUD RATE OF PRINTER AT 2400- and characters to 10/in

A

Options now: '1' will start program anew -not look for existing data  
 '2' existing data file will be read first

SELECTION? 2

B

On which of the following devices are you providing data?

cart(2)  
 ball and rail(3)  
 air track (5)

Device or option selection? 3

This trial will be identified as NUMBER 70

C

Time in seconds ? 1.53  
 Distance in meters? 1.65  
 Angle in degrees ? 6.2  
 Mass in kilograms ? .047  
 Has your data been entered correctly (1=yes; 0=no)? 1

| TRIAL         | DEVICE | ANGLE<br>[Deg.] | DISTANCE<br>[m] | MASS<br>[kg] | TIME<br>[s] | DIFF<br>[%] |
|---------------|--------|-----------------|-----------------|--------------|-------------|-------------|
| 70            | 3      | 6.2             | 1.65            | 0.047        | 1.53        | 33.2        |
| OTHER TRIALS: |        |                 |                 |              |             |             |
|               |        | 6.7             | 1.04            | 0.047        | 1.41        | 8.5         |
|               |        | 6.7             | 1.26            | 0.045        | 1.53        | 5.8         |
|               |        | 6.7             | 1.5             | 0.045        | 1.74        | 13.3        |
|               |        | 6.7             | 1.04            | 0.031        | 1.43        | 11.0        |
|               |        | 6.7             | 1.04            | 0.031        | 1.43        | 11.0        |
|               |        | 6.7             | 1.26            | 0.031        | 1.93        | 40.8        |
|               |        | 1.36            | 2.44            | 0.012        | 5.10        | 19.3        |
|               |        | 11.3            | 2.43            | 0.480        | 1.80        | 21.9        |
|               |        | 11.3            | 2.43            | 0.440        | 1.83        | 4.7         |
|               |        | 11.3            | 2.43            | 0.120        | 1.73        | 15.4        |
|               |        | 11.3            | 2.43            | 0.120        | 1.76        | 18.3        |
|               |        | 24.8            | 1.91            | 0.040        | 1.04        | 14.1        |
|               |        | 24.8            | 2.41            | 0.030        | 1.18        | 15.8        |
|               |        | 24.8            | 2.41            | 0.012        | 1.18        | 15.8        |
|               |        | 24.8            | 1.91            | 0.012        | 1.02        | 10.7        |
|               |        | 14.6            | 2.41            | 0.040        | 1.50        | 13.3        |
|               |        | 6.7             | 1.04            | 0.047        | 1.40        | 7.2         |

PRESS &lt;ENTER&gt; OR &lt;RETURN&gt; TO INPUT MORE DATA?

Figure 1

without incrementing the trial number.

A dotted line encircles section "D". This array of information is a screenful for computers operating under the CP/M operating system. This is the computer analysis of the student data and includes results from the most recent 17 trials using the same apparatus (device number 3 in this example). In this particular analysis, the calculated result requested of the student is not displayed. Rather, the student is informed of the absolute error of his or her result with respect to the theoretically expected result (the column labeled "DIFF"). The inclusion of other student results, including the report of how closely to the "expected" result other students came, enables the current program-user to place his or her results into that particular context.

In addition to entering particular data requested, there are two options exercizable at the beginning of the data-request cycle. Typing '999' overwrites the student-data file which existed at the beginning of the session or it creates one if none existed previously. When '10' is typed, all stored student data (including calculated results) beginning with the earliest record is printed out. Program control is always returned to the data-entry sequence.

The Program Listing for GRAVITY: Figure 2 is the BASIC listing of GRAVITY. The command "CLS" is non-operative; it is meant to signify "clear screen".

The first program line of operational consequence is Line 200. The use of "Arrays" and the "Dimensioning" of these arrays is a standard approach to retaining several values of a given variable within the execution of a program. In this case, one-dimensional arrays have been created for each variable so that both the number of variables as well as their names may be easily altered.

Lines 700-800: This section determines the terms under which the data may be sorted. Keyboard entries will be limited by the "sieve" statement in line 880. This point marks the beginning of the student-use cycle and thus was chosen as the point of instructor intervention.

Lines 820-860: Keyboard entries of '10' and '999' will produce printouts of all data and the saving-to-disk of all student data.

Line 880: Most programmers tend to limit user input to all computer prompts by "sieve" statements similar to this one. Such user error-trapping is difficult to do well because the programmer must anticipate



## PROGRAM LISTING FOR GRAVITY

```

100 ' PROGRAM NAME: GRAVITY (LAST REVISED: MAY, 1984)
120 ' AUTHOR: Norman H. Fredette, Fitchburg State College Physics Dept.
140 ' Fitchburg, MA. [USA] 01420
160 ' Interpreter/System: Microsoft BASIC ; Heath/Zenith H/Z-88
200 DIM G(300),DIFF(300),Y(300),M(300),AN(300),DI(300),T(300)
220 A$="#.###":B$="###.##":C$="##"
340 CLS:PRINT:PRINT:PRINT
400 ' -----REMINDERS TO THE INSTRUCTOR-USER
420 PRINT "PROGRAM OPERATION NOTES:"
440 PRINT " '999' at DEVICE input will dump to disc"
460 PRINT " '10' at DEVICE input will dump all data to printer"
480 PRINT " --SET BAUD RATE OF PRINTER AT 2400- and characters to 10/1n"
500 PRINT:PRINT
520 PRINT"Options now: '1' will start program anew --not look for existing data"
540 PRINT " '2' existing data file will be read first"
560 PRINT:PRINT:INPUT "SELECTION";Z: IF Z=2 THEN GOTO 1720
600 CLS:PRINT:PRINT:PRINT
700 ' -----STUDENT INPUT OF DATA
720 PRINT"On which of the following devices are you providing data?"
740 PRINT " cart(2)"
760 PRINT " ball and rail(3)"
780 PRINT " air track (5)"
800 PRINT:PRINT:INPUT "Device or option selection";Y[C]
820 ' -----INSTRUCTOR ASSUMPTION OF CONTROL FOLLOWS
840 IF Y[C]=10 THEN GOTO 2020
860 IF Y[C]=999 THEN GOTO 1840
880 IF Y[C]=2 OR Y[C]=3 OR Y[C]=5 THEN 900 ELSE PRINT E$;"PLEASE REENTER VALUE":GOTO 720
900 PRINT"This trial will be identified as NUMBER";C: "--SHOULD BE IN REVERSE VIDEO
920 PRINT
940 INPUT "Time in seconds ";T[C]
960 INPUT "Distance in meters";DI[C]
980 INPUT "Angle in degrees ";AN[C]
1000 INPUT "Mass in kilograms ";M[C]
1020 INPUT "Has your data been entered correctly (1=yes; 0=no)";Z
1040 IF Z=0 THEN CLS:PRINT "Enter data anew:"; :GOTO 920
1100 ' -----MATH MANIPULATION OF NEW STUDENT DATA
1120 G[C]=2*DI[C]/(SIN(AN[C]*3.1416/180)*[T[C]]^2)

```

Figure 2a

## Program Listing (cont)

```

1140 DIFF[C] = ABS([G[C]-9.8]/9.8)*100: CLS
1200 ' -----SCREEN PRINT OF ANALYSIS OF STUDENT'S OWN DATA
1220 PRINT" TRIAL DEVICE ANGLE DISTANCE MASS TIME DIFF"
1240 PRINT" [Deg.] [m] [kg] [s] [%]"
1260 PRINT TAB(5);C;
1280 PRINT TAB(12);Y[C];
1300 PRINT TAB(22);AN[C];
1320 PRINT TAB(31);DI[C];
1340 PRINT TAB(40);USING "#.###";M[C];
1360 PRINT TAB(48);USING A$; T[C];
1380 PRINT TAB(56);USING B$; DIFF[C]: PRINT
1420 ' -----SCREEN LISTING OF OTHER STUDENT DATA ON SAME DEVICE
1440 IF C=1 THEN GOTO 1540 ELSE PRINT P$;"OTHER TRIALS:";Q$
1460 X=1:FOR I=1 TO C-1:IF Y[I]=Y[C] AND X<18 THEN PRINT TAB(22);AN[I];TAB(31);DI[I];TAB(40);USING "#.###";M[I];
1480 IF Y[I]=Y[C] AND X<18 THEN PRINT TAB(48);USING A$;T[I];
1500 IF Y[I]=Y[C] AND X<18 THEN PRINT TAB(56);USING B$;DIFF[I]:X=X+1
1520 NEXT
1540 PRINT:INPUT "PRESS <ENTER> OR <RETURN> TO INPUT MORE DATA";D$
1560 C=C+1:GOTO 600
1700 ' -----READ STUDENT DATA SAVED IN PREVIOUS SESSIONS
1720 OPEN"I",1,"ROLL4.SAV":INPUT#1,C
1760 FOR I=1 TO C:INPUT#1, Y[I],DI[I],AN[I],M[I],T[I],G[I],DIFF[I]:NEXT
1780 CLOSE #1: C=C+1:GOTO 600
1820 ' -----SAVE CURRENTLY ENTERED DATA AS WELL AS ANY AT OUTSET
1840 OPEN"O",1,"ROLL4.SAV":C=C-1: WRITE#1,C
1880 FOR I=1 TO C:WRITE#1,Y[I],DI[I],AN[I],M[I],T[I],G[I],DIFF[I]:NEXT
1900 CLOSE #1:C=C+1: GOTO 720
2000 ' -----INSTRUCTOR OPTION TO PRINT ALL DATA
2020 PRINT E$:PRINT:PRINT:PRINT:PRINT P$;"IS PRINTER ON?";Q$
2040 LPRINT" TRIAL DEVICE ANGLE DISTANCE MASS TIME g(pred) DIFF"
2060 LPRINT" -----"
2080 FOR I=1 TO C-1:LPRINT TAB(5);I;TAB(12);Y[I];TAB(22);AN[I];TAB(31);DI[I];
2100 LPRINT TAB(40);USING "#.###";M[I];
2120 LPRINT TAB(47);USING A$;T[I];
2140 LPRINT TAB(54);USING B$;G[I];
2160 LPRINT TAB(62);USING B$;DIFF[I]:NEXT:GOTO 720
2180 END

```

Figure 2b

all inappropriate entries). Because I have experienced few problems associated with either user-confusion or inappropriate data-entry (the usual reasons why programmers use error-trapping), I often do not bother with sieve statements.

Lines 940-1000: Because I have had little success with prompts which request several pieces of data separated by commas, each prompt in this program is a request for one piece of data. Separate prompts for each variable also allow for easier transformation to another collection of variables.

Lines 1020-1040: This is an important option because students often confound their data entries; a fact which becomes obvious to them only when the entry process is complete. If the student enters '0', the trial number is not incremented and the entire query sequence is run through once more.

Lines 1100-1140: Here, the computer calculates the student result and compares it with the "accepted" value. The student is not informed of this calculated result in the screen-print which comes next.

Lines 1200-1380 include PRINT USING statements which are designed to accomplish two things: 1.) to limit the reported digits;; 2.) to "right-justify" the numbers for easier (more rapid) comparison. PRINT USING statements cannot be mixed on the same program line in this particular version of BASIC.

Lines 1420-1540: Produces a listing of other student trials. The number reported is limited to a screenful of both the student's own data and the most-recently entered data for the same device or procedure.

Lines 1700-1920: This sequence which produces the data transfer between computer and disc storage describe "sequential file" operations.

Lines 2000-2160: This sequence which provides a carry-away copy of all student data as well as program calculated results is intended mainly for the instructor.

Potential Benefits from the use of Data-Checking Programs: I have not only found several improvements in student laboratory work as the result of the use of this program and others like it but additionally have found it useful to my own instructional work and foresee a potential for researchers as well.

In terms of student benefits, a program such as the one presented here permit, and indeed encourages, student data-evaluation which:

- 1) can revolve about a reasonable quantity of data;
- 2.) takes place in the same session as that in which the work was done;
- 3.) includes meaningful information for evaluation of data-quality yet requires that the student manipulate his own values to determine the result required by the instructor;
- 4.) is not particularly ego-threatening to the student (the instructor will not be informed about any individual's "poor" results);
- 5.) is "officially" sanctioned (not clandestine).

Insofar as benefits to instructors are concerned, printouts may be used to evaluate a particular set of procedures in terms of its appropriateness in the instructional sequence. A review of student data for some interval (individual lab, day or whatever) can yield clues about whether or not the students were prepared for that particular investigation. One can also pick up on pieces of apparatus that are not working properly and effect a repair before the next class.

Researchers may also find its stored information useful. The program can be easily altered to allow the retention of separate student data sets as well as the accumulated data file (add another disc-write statement). A researcher can then compare the results of having varied any aspect of the course structure

#### Conclusion and Summary

I assume that the education of a person is a matter of enhancing the person's restructuring of their own conceptions of the physical world. Many educators believe that the restructuring process is a highly personalized one. The computer program presented here will provide the student with information which may be used to place his or her own data into a broader context. At the very least, students are encouraged to examine laboratory data other than the few pieces which they collect before constructing the laboratory report.

A computer program which may be easily altered with a word processor has been presented. This prototype was written so that numbers of variables, variable names, data-sorters, and the information provided the student could be altered with a minimum of effort.

I have found that, with a few hours of work, this program can be edited to produce similar programs for other experiments. Thus, writing this particular program has provided me an inexhaustible method for enhancing student learning though the use of an instrument which has

become increasingly available to physics instructors.

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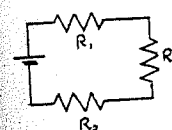
## Addendum to: The Use of Computers as a Student-Data Check (An Example Using Electric Circuits)

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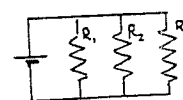
**Introduction:** In a previous paper (Fredette, 1984: "The Use of Computers as a Student-Data Check"), a claim was made that the program presented ("GRAVITY") could easily be revised for other laboratory experiments. In this brief paper, I present the original program edited by word-processor and alpha-tested to execute properly with "dummy" data.

The experiment for which this program was written was one in which the student is given three resistors along with a battery power supply and asked to arrange them in the following manner:

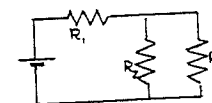
Circuit #1:



Circuit #2:



Circuit #3:



Measurements to be made in each case are:

1. The potential drop across the entire resistor combination in volts;
2. The current returning to the power supply in milliamperes.

**Student Use of the Program:** Students are told that when specific data requested in the program is entered, they will be presented with data obtained by other students working with the same circuit. Additionally, they will be given a quantitative evaluation of their data (as well as that of other students) with respect to the current expected if one is to consider only those aspects for which specific information was given. This evaluation is found in the column labeled "DIFF" and is given in the form of a percent. Once it is found that differences are reported even when very careful measurements have been made, a challenge may be issued to explain why these differences remain.

**Explanation of Figures to Come:** Figure 1 represents the information which will appear on the screen of the user terminal. Circled portions are those typed in by the program user. Figure 2 lists that information listed on the system printer when the '10' option is exercised at the "Device" request (see paper previously cited for further explanation). Figure 3 is the program listing.

Figure 1

On which of the following circuits are you providing data?  
 series [1]  
 parallel [2]  
 combination [3]

Enter number corresponding to circuit type ? 1  
 This trial will be identified as NUMBER 10

Value for R1? 1200  
 Value for R2? 1500  
 Value for R3? 1000  
 Current returning to source in milliamperes ? .69  
 Potential Drop across circuit in volts ? 2.9  
 Has your data been entered correctly [1=yes; 0=no]? 1

| TRIAL | CIRCUIT | POT.DR. | R1     | R2     | R3          | BAT. CURRENT | DIFF |
|-------|---------|---------|--------|--------|-------------|--------------|------|
| NO.   | [volts] | [ohms]  | [ohms] | [ohms] | [milliamp.] | [%]          |      |
| 10    | 1       | 2.9     | 1200   | 1500   | 1000        | .69          | 12   |

## OTHER TRIALS:

|     |      |      |      |     |    |
|-----|------|------|------|-----|----|
| 2.8 | 1200 | 1500 | 1000 | .79 | 4  |
| 1.4 | 460  | 1200 | 2000 | .35 | 9  |
| 1.5 | 500  | 460  | 1500 | .55 | 10 |
| 2.8 | 1000 | 5000 | 200  | .45 | 0  |
| 2.8 | 1000 | 2000 | 500  | .8  | 0  |
| 3   | 430  | 1250 | 1500 | .89 | 6  |

PRESS <ENTER> OR <RETURN> TO INPUT MORE DATA?

Figure 2

| TRIAL | CIRC.   | POT.DR. | R1     | R2     | R3     | BAT. CURR.  | DIFF CURR. | -COMP.      |
|-------|---------|---------|--------|--------|--------|-------------|------------|-------------|
| NO.   | [volts] | [ohms]  | [ohms] | [ohms] | [ohms] | [milliamp.] | [%]        | [milliamp.] |
| 1     | 1       | 2.8     | 1200   | 1500   | 1000   | .79         | 4          | 0.75676     |
| 2     | 1       | 1.4     | 460    | 1200   | 2000   | .35         | 9          | 0.38251     |
| 3     | 1       | 1.5     | 500    | 460    | 1500   | .55         | 10         | 0.60976     |
| 4     | 1       | 2.8     | 1000   | 5000   | 200    | .45         | 0          | 0.45161     |
| 5     | 1       | 2.8     | 1000   | 2000   | 500    | .8          | 0          | 0.80000     |
| 6     | 1       | 3       | 430    | 1250   | 1500   | .89         | 6          | 0.94340     |
| 7     | 2       | 3       | 1000   | 5000   | 120    | 26          | 9          | 28.60000    |
| 8     | 3       | 3       | 200    | 500    | 100    | 47          | 344        | 10.58820    |
| 9     | 3       | 1.5     | 250    | 320    | 100    | 4.3         | 6          | 4.59854     |
| 10    | 1       | 2.9     | 1200   | 1500   | 1000   | .69         | 12         | 0.78378     |

Figure 3  
PROGRAM LISTING

```

100 ' PROGRAM NAME: CIRCUIT (LAST REVISED: SEPTEMBER, 1984)
120 ' AUTHOR: Norman H. Fredette, Fitchburg State College Physics Dept.
140 ' Fitchburg, MA. [USA] 01420
160 ' Interpreter/System: Microsoft BASIC ; Heath/Zenith H/Z-8S
180 DEFINT C,Y,I,X,Z:C=1
190 ' Variables: Resistor #1 =T; Resistor #2 =DI; Resistor #3 =AN
195 ' Current[student meas.] = M; Circuit voltage =VO
197 ' Current calculated by computer= AG
200 DIM DIFF(300),Y(300),M(300),AN(300),DI(300),T(300),VO(300),AG(300)
220 AS="###":BS="###":CS="###"
340 CLS:PRINT:PRINT
400 ' -----REMINDERS TO THE INSTRUCTOR-USER
420 PRINT "PROGRAM OPERATION NOTES:"
440 PRINT " '999' at DEVICE input will dump to disc"
460 PRINT " '10' at DEVICE input will dump all data to printer"
480 PRINT " --SET BAUD RATE OF PRINTER AT 2400- and characters to 10/in"
500 PRINT:PRINT:PRINT"Options now: '1' will start program anew -not look
for existing data"
540 PRINT " '2' existing data file will be read first"
580 PRINT:PRINT:INPUT "SELECTION";Z: IF Z=2 THEN GOTO 1720
600 CLS:PRINT:PRINT
700 ' -----STUDENT INPUT OF DATA
720 PRINT"On which of the following circuits are you providing data?"
740 PRINT " series [1]"
760 PRINT " parallel [2]"
780 PRINT " combination [3]"
800 PRINT:INPUT "Enter number corresponding to circuit type ";Y(C)
820 ' -----INSTRUCTOR ASSUMPTION OF CONTROL FOLLOWS
840 IF Y(C)=1 THEN GOTO 2020
860 IF Y(C)=999 THEN GOTO 1640
880 IF Y(C)=1 OR Y(C)=2 OR Y(C)=3 THEN 900 ELSE CLS:PRINT"PLEASE
REENTER VALUE";GOTO 720
900 PRINT"This trial will be identified as NUMBER";P$;C;Q$
940 PRINT: INPUT "Value for R1";T(C)
960 INPUT "Value for R2";DI(C)
980 INPUT "Value for R3";AN(C)
1000 INPUT "Current returning to source in milliamperes ";M(C)
1010 INPUT "Potential Drop across circuit in volts ";VO(C)
1020 INPUT "Has your data been entered correctly [1=yes; 0=no]";Z
1040 IF Z=0 THEN PRINT ES;"Enter data anew:"; ;GOTO 920
1100 IF Y(C)=1 THEN AG(C)=VO(C)/(T(C)+DI(C)+AN(C))
1110 IF Y(C)=2 THEN AG(C)=VO(C)/(T(C)*DI(C)*AN(C)/(T(C)*DI(C)+T(C)*AN(C)
+AN(C)*DI(C)))
1120 IF Y(C)=3 THEN AG(C)=VO(C)/(T(C)+(DI(C)*AN(C)/(DI(C)+AN(C)))
1130 AG(C)=AG(C)*1000
1140 DIFF(C) = 100*ABS((AG(C)-M(C))/AG(C))
1200 ' -----SCREEN PRINT OF ANALYSIS OF STUDENT'S OWN DATA

```

```

1220 CLS: PRINT"TRIAL CIRCUIT POT.DR.   R1   R2   R3   BAT. CURRENT
DIFF"
1240 PRINT"      NO.   [volts] [ohms] [ohms] [ohms] [milliamp.] [%]
1260 PRINT TAB(3);C;
1280 PRINT TAB(9);Y[C];
1290 PRINT TAB(16);VO[C];
1300 PRINT TAB(24);T[C];
1320 PRINT TAB(31);DI[C];
1340 PRINT TAB(38);AN[C];
1360 PRINT TAB(46);M[C];
1380 PRINT TAB(53);USING C$; DIFF[C]
1420 '-----SCREEN LISTING OF OTHER STUDENT DATA ON SAME DEVICE
1440 PRINT:IF C=1 THEN GOTO 1540 ELSE PRINT" OTHER TRIALS:";
1460 X=1:FOR I=1 TO C-1:IF Y[I]=Y[C] AND X<18 THEN PRINT TAB(16);VO[I];
TAB(24);T[I];TAB(31);DI[I];
1480 IF Y[I]=Y[C] AND X<18 THEN PRINT TAB(38);AN[I];TAB(46);M[I];
1500 IF Y[I]=Y[C] AND X<18 THEN PRINT TAB(53);USING C$;DIFF[I]:X=X+1
1540 NEXT:PRINT:INPUT "PRESS <ENTER> OR <RETURN> TO INPUT MORE DATA";D$
1560 C=C+1:GOTO 600
1700 '-----READ STUDENT DATA SAVED IN PREVIOUS SESSIONS
1720 OPEN"1",1,"CIRCUIT.SAV"
1740 INPUT#1,C
1760 FOR I=1 TO C
1770 INPUT#1, Y[I],DI[I],AN[I],M[I],T[I],VO[I],AG[I],DIFF[I]:NEXT
1780 CLOSE #1
1800 C=C+1:GOTO 600
1820 '-----SAVE CURRENTLY ENTERED DATA AS WELL AS ANY AT OUTSET
1840 OPEN"0",1,"CIRCUIT.SAV":C=C-1
1860 WRITE#1,C
1880 FOR I=1 TO C
1895 WRITE#1,Y[I],DI[I],AN[I],M[I],T[I],VO[I],AG[I],DIFF[I]:NEXT
1900 CLOSE #1:C=C+1:GOTO 720
2000 '-----INSTRUCTOR OPTION TO PRINT ALL DATA
2020 CLS:PRINT:PRINT:PRINT:PRINT "IS PRINTER ON?";
2220 LPRINT"TRIAL CIRCUIT POT.DR.   R1   R2   R3   BAT. CURRENT
DIFF CURRENT-COMP."
2240 LPRINT"      NO.   [volts] [ohms] [ohms] [ohms] [milliamp.] [%]
[milliamp.]
2250 LPRINT:FOR I=1 TO C-1
2260 LPRINT TAB(3);I;
2280 LPRINT TAB(9);Y[I];
2290 LPRINT TAB(16);VO[I];
2300 LPRINT TAB(24);T[I];
2320 LPRINT TAB(31);DI[I];
2340 LPRINT TAB(38);AN[I];
2360 LPRINT TAB(46);M[I];
2380 LPRINT TAB(53);USING C$; DIFF[I];
2400 LPRINT TAB(65);USING B$;AG[I]:NEXT:C=C-1:GOTO 720
2500 END

```

## The energy flow in the electric circuit

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### 1. Introduction

The purpose of power lines is not to provide electrons a possibility of moving through wires but to transmit energy from a point A to a more or less distant other point B. As interesting as it may be to study the conduction of charge carriers through solid matter, the motive forces acting upon them in batteries or generators etc, one should always pay due regard to the fact that electric currents are accompanied by energy transport. It is this capability of easily transmitting and distributing energy electrical installations are usually built for.

We therefore believe that teaching even the elements of the electric circuit must comprise the concept of energy and energy flow. The teacher and (a fortiori) the teacher's teacher therefore have to be acquainted with different stages of describing and modelling energy flow in the electric circuit.

Physicists usually seem to prefer the picture given by Poynting (1884)<sup>1)</sup>, based upon Faraday's and Maxwell's concepts of electric and magnetic fields. It is certainly worthwhile to apply Poynting's picture of energy flow to different arrangements of conductors and circuits, taking into account not only qualitative but also quantitative aspects, which has been done by many authors recently and in the past<sup>2)</sup>. However, the main goal of this paper is not to give a detailed description of the energy flow in a certain circuit by means of Poynting's vector, it is my intention to remind you, my colleagues, to the facts that

- Poynting's vector is by no means a unique (neither mathematically nor empirically) kind of describing electric energy flow
- there are other possibilities (and have been given by a

series of authors) of constructing expressions of field components and/or potentials, describing one and the same physical situation other than Poynting's, and expressing quite different pictures as to where the energy flows and where not,

- that these different pictures are mutually equivalent and may not be decided on by physical or empirical arguments alone
- last but not least, nobody has to worry about fields, vector algebra and vector analysis and the "real" flow of energy if he wishes to teach energy flow aspects of the circuit to students who do not possess elaborate mathematical tools.

However I do not intend to curtail in the least the elegance and the importance of Poynting's method, an invention seeing its 100<sup>th</sup> anniversary just in this year.

## 2. Phenomena (simple dc-case)

The elements of the simple circuit are: the source (battery, generator, etc.), the sink (generally a resistor) both separated in space, and the transmission line as the link between them. The phenomenon to be described is as follows: energy is transmitted from the source to the sink at the rate (neglecting losses)

$$P = UI$$

where  $U$  is the voltage of the battery and  $I$  the current of the transmission line. The source of course is no source of electric charge. The role of the transmission line is somewhat mysterious. At least it is clear that transmission of energy stops as soon as the line is interrupted. In this sense one might be inclined to talk of the energy as being "wired". Let us, for the moment, forget things we have learnt about electricity, especially the term electric energy. Let us try to imagine the reasoning of people of pre-electricity-times, of times where electrical installations were not abundant. My late father, who was in his first grade in 1910, has told me that some day people erected strange

poles along the streets of his little hometown, connecting them by copper wires, thereby being able to illuminate houses without consuming kerosene. He also mentioned that he then has not been able to figure out how this might work. Learned people of the time might have reasoned on the following lines: what we now call the source is a sink of energy (of course, a central power plant is a big sink of fuel), and there are many sources (what we now call the sinks) of various kinds of energies (mechanical, chemical, heat, light, etc.) altogether linked to the power plants by transmission lines.

It seems reasonable to assume that energy does not disappear at the power station and reappear in the household but is transmitted by and along the transmission line. How this works, if it is the plus-wire or the minus-wire (one of them might even be omitted and substituted by ground) who bears the burden is not altogether clear.

Again let me cite my late father. He has worked as a mechanic, being a locksmith by profession in a power plant for more than 45 years. He knew by experience the diameters of steam pipes necessary to drive turbines with a power output up to 100 MW. When, in the late sixties, steam on the railroads was superseded by electricity in this country, when there appeared locomotives on the rails driven by electricity, powered with 10 MW-engines, sucking their needs out of a wire of less than one half of an inch diameter, my father asked me: "How is it possible to drive as much power through a wire as thin. I do not understand. Do you?"

## 3. Technician's picture:

### Description of energy flow without fields (Non-Maxwellian point of view)

According to this kind of reasoning energy transport is effected by means of the moving charge carriers making up the current in the wire. They not only carry electrical charge but also electrical energy. This electrical energy however does not adhere inseparable to the carrier as is the

case with the charge, but is packed upon it in the source and unpacked in the consumer of electricity. More specific the charge carrier gains energy<sup>3)</sup> passing through the battery by an amount of

$$\Delta W = \Delta Q U$$

where  $\Delta Q$  is its electrical charge and  $U$  again the source voltage. The mechanism is similar to the gaining of gravitational energy of water droplets in the process of cloud development. Together with the carriers energy is transmitted not only by but even through the wire to the consumer, where it is used for various purposes. The carriers, emptied of energy, return to the source to begin another cycle like the lorries of a suspension railway. A somewhat more detailed inspection shows that not all of the energy gained by the carriers in the source really reaches the sink. A certain amount is used up for driving the carriers and therefore the voltage at the consumer is less than at the battery. It is also conventional reasoning to assume, that all of the energy available at the consumer's site is unloaded. One may equally well assume that part of it is returning with the carriers into the source thereby using the minus-wire as well as the plus-wire for energy transport. The essential point of this picture is: only the interior of the wires carries the energy flow, not their surroundings, consisting either of insulating matter or empty space. Energy is totally "wired". In accordance to this picture the load capacity of a line is dependent totally on properties of the conductors not of the surrounding insulators.

#### 4. Poynting's picture<sup>4)</sup>

It is the nonconducting space surrounding the wires of the line that carries the energy flow using this picture. This space, containing electric and magnetic fields in accordance to the distribution of charges and currents on the wires and obeying Gauß's and Ampere's laws is the theatre of energy flow, the density of which is given by the well-known expression

$$\vec{S}_p = \vec{E} \times \vec{H}$$

("P" for Poynting).

Moreover the mutual potential energies of charges and currents are considered not to be localized upon themselves but distributed in space possessing the energy density

$$\frac{1}{2}(\vec{E} \cdot \vec{D} + \vec{B} \cdot \vec{H})$$

Some of the more important properties of Poynting's vector field are:

- the total flux of  $\vec{S}_p$  out of any closed surface containing the source is just the power delivered by the source;
- only those parts of the surface that do not intersect current-carrying conductors give a contribution to this flux whilst those parts through which currents go are free of any energy flow;
- for a good transmission line  $\vec{S}_p$  is very nearly zero inside the wires, nonzero only outside, directed in general parallel to the line axis;
- as the field strengths decrease with increasing distance from the line so does Poynting's vector a fortiori; consequently it is only a narrow hose of nonconducting space in the direct surroundings of the line that carries the energy flow;
- taking into account line losses the interior of wires still is free of any  $\vec{S}_p$  parallel to the axis of the line, but there is indeed some  $\vec{S}_p$  normal to this axis carrying the equivalent of Joule's heat from the exterior through the surface of the wires.

Paying due regard to these properties, having analyzed the straight wire Sommerfeld<sup>5)</sup> concludes:

Therefore the conductor of the electric current is an insulator of energy flow and vice versa the electric insulator is a conductor of energy flow.

#### 5. Equivalence of the two pictures

Poynting's picture recently has received broad attention by some authors as a means of describing the mecha-

nism of energy flow in the circuit. Moreover, some of them seem to prefer it as being the only correct mapping of reality. If this were true teachers who want to teach energy flow to students who do not possess elaborate mathematical techniques should have reasons to worry.

Fortunately this view of Poynting's picture is not true. It is one of many possible ones. In the case of the dc-circuit it is a simple matter of vector analysis to show its equivalence with the technician's description<sup>6)</sup>.

Let

$$\begin{aligned}\vec{\nabla} \times \vec{E} &= -\dot{\vec{B}} & \vec{\nabla} \cdot \vec{D} &= \rho \\ \vec{\nabla} \times \vec{H} &= \vec{j} + \dot{\vec{D}} & \vec{\nabla} \cdot \vec{B} &= 0\end{aligned}$$

be the set of Maxwellian equations.

Let

$$\vec{E} = -(\vec{\nabla}\varphi + \dot{\vec{A}}), \quad \vec{B} = \vec{\nabla} \times \vec{A}$$

$\varphi, \vec{A}$  the potentials.

Then

$$\begin{aligned}P &= \int d\vec{o} \cdot \vec{E} \times \vec{H} \\ &= -\int d\vec{o} \cdot (\vec{\nabla}\varphi \times \vec{H}) \\ &= -\int d\vec{o} \cdot \vec{\nabla} \times (\varphi \vec{H}) + \int d\vec{o} \cdot \varphi \vec{\nabla} \times \vec{H}\end{aligned}$$

$$\sim P = \int d\vec{o} \cdot \vec{j} \varphi$$

As well the expression

$$\vec{S}_p = \vec{E} \times \vec{H}$$

which is zero inside wires as

$$\vec{S}_T = \vec{j} \varphi$$

("T" for technician)

which is zero outside wires is therefore a possible descrip-

tion of energy transport by a transmission line. We do not see a possibility of preferring one or the other on empirical grounds alone.

#### 6. Simple circuit: ac-case

Still both pictures may be used, yet the proof of equivalence has to be modified according to time-dependent terms. Therefore

$$\begin{aligned}P &= \int d\vec{o} \cdot \vec{E} \times \vec{H} \\ &= \int d\vec{o} \cdot (\vec{j} \varphi + \varphi \dot{\vec{D}} - \dot{\vec{A}} \times \vec{H})\end{aligned}$$

which leads to an alternate expression of the density of energy flux<sup>7)</sup>, namely.

$$\vec{S}_L = \vec{j} \varphi + \varphi \dot{\vec{D}} - \dot{\vec{A}} \times \vec{H}.$$

("L" for Lai)

In case of a quasistationary situation and by properly gauging the potentials each of the terms may be interpreted as follows:

$-\vec{j} \varphi$  is the energy flux carried by and through the wires (wired flux).

$-\varphi \dot{\vec{D}} + \dot{\vec{A}} \times \vec{H}$  might be called "wireless" energy flux, representing flux of electric and magnetic energies out of wires into space.

These latter terms provide for the amounts of energy necessary for charging and discharging the capacitance and inductance respectively of the line proper. In contrast to Poynting's picture these amounts of energy (blind-power of the line) are transmitted through the wires, emanating normally out of their surface into space (charging circle).

#### 7. Summary and conclusions

Taking the simple circuit as an example we showed that Poynting's expression of energy flow by no means is the only possible one. This fact, the nonuniqueness of the Poynting



vector, has been common knowledge ever since the general reception of Faraday-Maxwell's electromagnetic theory at the beginning of this century.

For instance Drude<sup>8)</sup> stated the case very clearly in his textbook: the law of local energy conservation only permits an expression for the density of energy flow that is determined up to a field that has only to be divergence-free. In other words, if a certain field of energy flow will describe a given situation, one may add any field where energy is streaming in closed curves (i.e. the curl of another field) and that resultant field will also do.

For some time and by some authors this situation has been considered unsatisfactory. There have been attempts to show the "reality" of Poynting's vector, using additional arguments. There have been other attempts to establish other expressions to be preferred to Poynting's or more "real"<sup>9)</sup>. For us it seems to be clear that an expression for local energy flow is not determined uniquely by Maxwell's equation and energy conservation. Moreover, this is even true for the expression of energy density proper<sup>10)</sup>. This is no drawback for a teacher, on the contrary, he is regaining liberty of choices.

Of course, this nonuniqueness of expressions for local energy density respectively flow is not confined to the case of electromagnetic energy. It has to do, in our opinion, with peculiar difficulties in the concepts of energy localization and energy transport. Indeed, it is no simple task to decide where the energy of a system of interacting bodies is situated: upon the bodies or in the fields originating in the bodies or on both of them. To illustrate the difficulty let us imagine a paradox world, different from ours in this respect: imagine that hydrocarbon fuels would be distributed (as gases) abundantly in the atmosphere, not being deposited in remote and rare accumulations, and imagine too that oxygen would be accumulated at rare remote and subterranean deposits like fuels in our world, had to be transported by tankers and pipelines to centers of con-

sumption. I bet that in this imaginary world people would consider the oxygen as being the carrier of energy. Now, where is chemical energy we use by burning fossile fuels "really" situated: in the oilfields, on the atmospheric oxygen or in the space in between?

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Fields that accompany currents

by Adolf Walz

At first, let me give some definitions of the concepts that I will use.

Current: That is the collective movement of charged particles. We will consider only currents in the narrow channels of wires. Therefore the following thoughts are limited to movements of electron collectives. I will name such a collective "electron-fluid" in agreement with quantum physics: electrons in wires configure a very strong coupled collective. In most cases we can consider that as being an almost incompressible liquid with some special properties.

Charge: Something inherent in some sorts of elementary particles. In my opinion these particles are not charges but charge carriers. The collective movement of charge carriers is the electric current. The charge flow per second through a cross section of a channel is a good measurement of the intensity of the current on that point.

Circuits: In elementary physics we mostly consider closed circuits. These are circuits where the charge carriers move around endlessly until the switch is opened. (This means we are not confronted with displacement currents.)

Energy flow: Usually circuits have the purpose of transferring energy from one point of space to another. This works well because every circulating charge flow is accompanied by energy flow. Whereas the electron-fluid moves like a merry-go-round, the

energy is streaming from the so called source (a device that transforms some sort of energy into electric energy) to the sink at a distance (which works in the opposite way). The localisation of the flowing energy is a very complicated problem we will not deal with in that context.

The word current in everyday-language has several meanings: (1) charge (2) collective charge movement, (3) energy, (4) energy flow. This multiple meaning limits the endeavour of physics teachers to create a consistent image of the processes in circuits in the minds of pupils and students. Therefore we should avoid such confusion during our lessons by using the correct expressions 'charge' and 'chargeflow' (= current) on one side, 'energy' and 'energy flow' on the other. We then should demand our students to do likewise. Only persons who are used to differentiating so carefully can understand the right meaning of "current" in specific contexts.

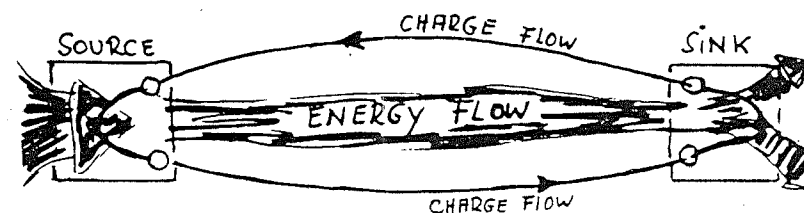
### Electric fields

You are all familiar with the magnetic field that accompanies current. The physics teaching at universities is very successful in that area. In addition, one can get any desired information from highschool textbooks. Therefore I will leave this subject in order to shorten my comments. However, it's quite a different thing with respect to electric fields in and around electric circuits. These are areas not usually treated in either textbooks or even at university level. But, they are indispensable for the understanding of events in circuits and their dynamics.

In agreement with Ohm's law, inside a wire there must be an almost homogeneous field which runs parallel to the axis, satisfying the equation

$$j = \sigma \cdot E = \text{constant.}$$

This E-field pushes the electron-fluid in a certain direction. It is therefore responsible for the collective movement of the electrons, i.e. the current. One electron experiences the force  $F = e \cdot E$ . It thereby gains kinetic energy of the amount  $F = e \cdot E \cdot \Delta x$  from the field. The same amount of energy is delivered along  $\Delta x$  to the atoms of the metallic grid. There it manifests itself as heat. (You can imagine the energy transition from the fluid to the grid as taking place in form of randomly happening bumps between electrons and atoms).



1a: The two "flows" in a simple electric circuit



1b: Some circuit configurations

This happens only to a minor extent in the wires of a source (imagine an inductive one) and inside the transfer line between source and sink. But in the sink itself (e.g. an electric heater) it is the major effect. There we have an intensive E-field along a considerable distance. (The complications in the source we will discuss later). - Where do those important fields come from?

Are they generated by charges (+ and -) placed somewhere in or at the source, for instance at the poles? If you have a look at figure 1 you will have to reject that idea for most circuit-configurations: Faraway charges cannot produce fields for meandering wires.

Are variations in charge density inside the wire responsible for these fields? In that case we would have to assume that charge density increases towards the + pole and decreases towards the - pole. But such an assumption is invalid because of Coulomb's law expressed in the equation

$$\text{div } E = \rho / \epsilon_0$$

which would lead to a field with divergence not equal to zero. Divergence not equal to zero implies that there would be an inhomogeneous field inside the wire, with some field-lines originating at net charges. - In other words, it is impossible to explain the necessary field configuration with charge variations inside the wire because homogeneous fields and "streamlined" fields require  $\text{div } E = 0$  and therefore  $\rho = 0$ .

The only conception that matches our conditions consists in assuming that the field generating charges are located at the surface of the wire. Then we have divergence inside the wire equal zero and from there we can see a solution of the meander-problem.

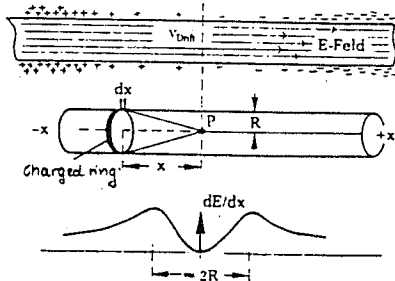
### Surface Charges

Let us now discuss what sort of charge distribution on the surface of a wire can generate a "streamlined" field inside. First we will limit the discussion to a long, thin, homogeneous, straight, ohmic wire. Inside this wire we already need a steady current. (The starting process of this current which is identical to the initial configuration of the surface charge distribution cannot be discussed in an incipient approach to the problem and will be neglected here.

1. If a wire is already in an E-field area before the current starts then this field will move electrons from some places to others. About a microsecond later the displacement will be finished. You then have charges on the surface of the wire. But there are no net charge and no field inside and therefore neither any current. This static charge distribution may overlay the distribution responsible for currents. Usually the influenced charge density exceeds that of the current-generating charge density by some powers of ten. But, for the discussion of the dynamics of electron movement it can be neglected.
2. The surface charge distribution that generates a homogeneous axial-directed field in our long ohmic wire must be symmetrical to any point at the axis. Uniform charge density at the surface would fulfil that condition, but would not generate a field inside because lefthand- and righthand- effects compensate each other. - The next lower symmetrical configuration already generates the requested field: Imagine the wire-surface as consisting of uniformly charged narrow rings. Pick out a point at the axis (P). The ring at that position has a certain charge. If you now move along the wire to the right, you will touch rings with ever

increasing charge. If you move left, the charge decreases from one ring to the next (decrease in charge = less - or more +). Figure 2 shows to what extent the contribution of a certain ring to the inside field depends on its location. Thus you see that the major contribution comes from the neighbourhood on the left and the right, thus explaining the meander-problem. Some computation will show that the same concept holds for every point inside the wire and that the charge differences between neighbored rings are very small. For copperwires and technical current densities ( $10 \text{ A/mm}^2$ ) this difference amounts to the charge of as little as 100 electrons. In wires used for heaters and resistors this amount is somewhat larger.

$$\frac{d\vec{E}}{dx} = \frac{1}{4\pi\epsilon_0} \cdot \frac{C \cdot \vec{x} \cdot 2\pi r \cdot \vec{x}}{R^2 + x^2 \sqrt{R^2 + x^2}}$$

$$E_{\text{axis}} = \frac{C \cdot R}{\epsilon_0} \int_{-x}^{+x} \frac{x^2 dx}{(R^2 + x^2)^{3/2}}$$


2. Field in and charges on a straight wire

3. If you have conductors in the circuit which become narrower or wider everything that we said holds true with the exception that at such locations the charge distribution is more complicated. The same is valid for bends and corners: There are no netcharges in-

side, the whole field is generated by surface charges. - Naturally, there is an exception. If you have changes in conductivity, for instance, if you have connected a copper and an iron wire, you will get space charges inside, a + layer and a - layer left and right of the cross-section where the connection takes place. These layers are there without any current, due to electron-diffusion. If there is current, the layers will change in a complicated manner.

### Fields in sources

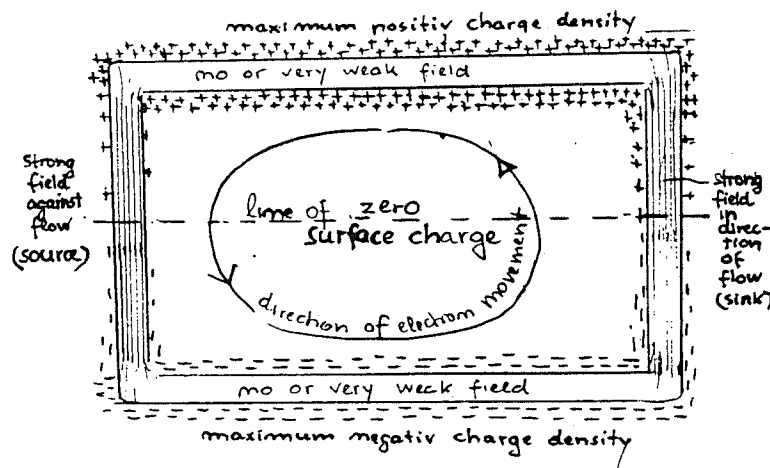
There is no way of increasing the surface density of charges all around the circuit. Therefore there must be a maximum density (+) at some point and a minimum density (-) at another. Between these two points, density variation and field direction must have the reverse sign. This takes place in the source. There the field generated by surface charges drives the fluid in the "wrong" direction. In order to get a steady current the electrons must experience an extra force.

1. Belt generator: In that machine electrons are sprayed to the insulating belt and transported against electric field forces to the - pole of the machine by the engine.

2. Generator which works by induction: The changing magnetic field forces the electrons to move against the E-field which is generated by surface charges on the wires of the generator.

3. Chemo-electric sources (battery-cells): The electron driving forces are of thermodynamical nature and occur in the layers where metal and electrolyte touch each other. - The same configuration is found in thermoelectric devices (metal-metal) and in the np- or

pn- transitions of semiconductors. The active fields here are constrained on atomic dimensions. Remember that you have at least two such transitions acting against each other. There has to be some assymetry in a real source!



3. Charges on the surface and fields in the wires of a circuit

The fields inside the wires of a circuit are sketched in figure 3. In addition, I have tried to show the charges on the surface that create these fields. Think of the source as a wire slowly moved in a strong homogeneous magnetic field and of the sink as an ohmic wire. The parallel power line is assumed nearly to be without resistance. The electrons in that circuit are pushed against the field in the source. There they gain potential energy. This energy

flows into the field. - In the wires of the power line the fluid moves with very low impediment. We have only a very weak field there. - In the sink the field is strong. Contrary to what happens in the source, the electrons are here pushed in the direction of their movement. By "falling down" in this field they gain kinetic energy which they hand over to the metal.

### Voltage

The push against the field in the source, e.g. the "sum of the field", characterises the energy transfer properties of this device. In the same way the "sum of the field" in the sink is responsible for the energy transfer properties of the sink. In my opinion, this in some respect ominous "sum of a field" corresponds exactly to what we know as voltage, which is

$$U_{12} = \int_1^2 \mathbf{E} \cdot d\mathbf{s}$$

You easily realise that the sum of all the pushes around the circuit has to be zero. There is no problem to differentiate between ohmic voltages and e.m.f's (electro motoric forces)! Neither have you difficulties to get an idea of the distribution of voltage along a circuit with serial resistors! Moreover, no problems exhibit by studying circuits with branches! - The outlined conception is consistent and very important, I think, firstly, for learning to differentiate between current intensity and voltage and, secondly, to get a lasting understanding of what is happening in circuits. This insights may be helpful for various didactic decisions.

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